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Methods of Obtaining Soil Strength Data for Modelling Vehicle Trafficability on Beaches

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DSTO-GD-0299

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ABSTRACT

Estimates of vehicle mobility or trafficability over beaches are useful for the planning of amphibious operations. If the bearing capacity of a beach is too small, then beach matting, which is heavy and bulky, needs to be transported. If the bearing capacity is large enough then the matting can be left behind, saving space and time. Bearing capacity also effects the speed at which vehicles can transit the beach. A widely used model for predicting mobility is the NATO Reference Mobility Model, version II, (NRMM II). The most critical parameter for mobility forecasts in this and similar models is sediment strength as determined by the cone index, CI, which is the resistance to penetration by soil of a standard shaped cone in pounds per square inch. The methods of obtaining CI are reviewed in this report. The best way is to use a cone penetrometer directly, but there are other less direct methods available and these are discussed.

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Published by

DSTO Aeronautical and Maritime Research Laboratory
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-012-010
September 2001

APPROVED FOR PUBLIC RELEASE

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Executive Summary

When vehicles are being offloaded from landing craft, during amphibious operations, it is important to know the bearing capacity of a beach's surface. If the beach is too soft for the types of vehicles being used, then matting has to be carried ashore and laid out. However if it is known that the beach is sufficiently firm then this bulky and heavy equipment does not have to be transported, and both space and time can be saved.

A commonly used model for predicting vehicle mobility is the NATO Reference Mobility Model, version 2, (NRMM II). In NRMM II and similar models the sediment strength, as measured by the cone index, CI, is the most critical soil parameter. In this report the different methods of obtaining CI are reviewed. The most reliable method is to use a cone penetrometer and the best of these appears to be the one developed by Stoll and others at Columbia University (Stoll et al., 1998). This was developed specifically for beach trafficability measurements. It records penetration resistance versus depth and can be used both on the beach and in shallow water, up to several meters depth. It has been used by divers in the surf zone and in NATO Exercises "Rapid Response 97 and 98". If such a direct method is not possible, less accurate (but still useful estimates) can be obtained by other methods. Of these the best is to use regression formulae between CI and grain size and beach slope. The remaining methods are really more qualitative but can be a useful guide.

Contents

1. Introduction

In amphibious operations, when vehicles are offloaded from a landing craft onto a beach, it is important to know whether or not the beach surface can carry the load. Beach matting is commonly laid to prevent bogging but it is bulky and heavy and takes up scarce room in landing craft. If a beach's surface is sufficiently firm to carry the vehicles to be disembarked then both space and time can be saved.

Both the US and UK militaries have been using vehicle mobility models for many years and the principal soil parameter is the soil strength, CI, as measured by a cone penetrometer (Larminie, 1988). CI stands for Cone Index and is the resistance by soil to penetration of a standard shaped cone, in pounds per square inch (Wong, 1989). Cone Index has its limitations as an index for soil properties (Wong, 1989) but is still the most practical parameter for soil strength. The NATO Reference Mobility Model (NRMM) is widely used by the NATO countries. It models the responses of vehicles and drivers to a whole range of terrain conditions - vegetation, gradients and soil types (Duell, 1982; Priddy, 1995).

Soil or sediment parameters used in NRMM are:

a) soil strength as either (i) rating cone index, RCI (where RCI = CI x RI, and RI = Remoulding Index = ratio of thoroughly disturbed to undisturbed soil strength) or (ii) simply as one of four broad classes, which are:

1, dry, (two driest months of the year);
2, wet, (two wettest months of the year);
3, average, (remaining eight months of the year);
4, wet-wet, (above normal wet month).

These last seem rather hard to apply to beaches which can vary between saturated in the swash zone to very dry towards the back of the beach. They were developed in the USA and appear to be fairly arbitrary classifications and quite empirical.

b) soil type listed as:

1 = fine-grained (a soil for which more than 50% of the grains, by weight, will pass through a sieve with 0.074 mm mesh).

2 = coarse grained (a soil for which more than 50% of the grains, by weight, will be retained on a sieve with 0.074 mm mesh).

3 = muskeg (a Canadian term for a swamp or bog containing organic soil with a surface layer of living vegetation and a sublayer of peat of any depth).

4 = impervious high plasticity[1] clay.

c) height of soil surface roughness e.g. ruts, hummocks, etc. (This is relevant to speed of movement, not soil bearing capacity).

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[1] Plasticity of a fine grained soil refers to its ability to undergo unrecoverable deformation at constant volume without cracking or crumbling.

For sandy beaches RI = 1, and only soil types 1 and 2 are relevant.

A two-dimensional vehicle-media interaction (VMI) model (Creighton and Walker, 1998) has been developed more recently at the US Army Engineers Waterways Experiment Station. This uses as inputs the soil parameters: CI, RI and soil density. Of these the most critical is CI. UK models also use RCI (Larminie, 1988).

All these models depend on cone index, which in some circumstances is not easy to obtain, plus soil descriptions, which are relatively easy to obtain. This report will therefore focus on means of obtaining the cone index, CI, on beaches. The zone of current interest extends from the back of a beach seawards to water depths of one to two metres, i.e. the zone over which disembarked vehicles may have to operate on a beach. In such a range the sand can vary from being fully saturated with water to totally dry. Below the water line the sand may contain bubbles of air which can strongly affect its properties. This report does not consider beaches made of very coarse materials made of pebbles, cobbles or other material with a diameter greater than about 60 mm.

2. Cone Penetrometers

Cone penetrometers, which are used to obtain values of cone index, CI, have been used in soil science since they were developed by the Waterways Experiment Station in World War II (Wong, 1989). The earliest version was a handheld device, such as that illustrated in Figure 1, and these are still being manufactured. In the 1950s and 1960s analogue recorders were attached to cone penetrometers to record both the resistance to penetration and penetration depth. Hence profiles of resistance versus depth could be obtained. In the 1980s digital recording devices were attached to cone penetrometers (Morrison and Bartek, 1986).

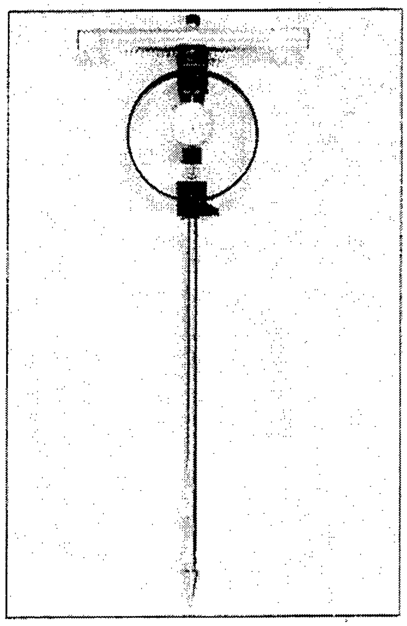

Figure 1. Proving Ring Penetrometer, from ELE International.

Examples of current digitally recording cone penetrometers are those made by Agridry Rimik of Australia (http://www.arpl.com.au) and Soil Measurement Systems of USA (http://www.soilmeasurement.com/). Both these instruments use an ultrasonic signal to measure penetration depth, and store their data internally for downloading later to a PC. Recently Professor R.D. Stoll of Columbia University, New York, with his colleagues, has developed a digitally recording cone penetrometer specifically for beach trafficability measurements (Stoll et al., 1998). It records penetration resistance versus depth and can be used both on the beach and in shallow water, up to several meters depth. It has been used by divers in the surf zone and in NATO Exercises "Rapid Response 97 and 98".

3. Inferring Cone Index from Other Data

It may not always be possible to obtain cone index (CI) values directly, in which case it has to be estimated from other parameters. Techniques for doing this were reviewed in Jenkins (1985) and are only summarised here. For more details Jenkins' report should be consulted. The methods for estimating CI can be grouped under six headings:

1.) using soil groups and soil water content;
2.) using grain size and, if it is available, beach slope;
3.) estimating grain size from water depth, wave height and period, at the surf break point, and using this grain size to estimate CI;
4.) using a diver's Miniature Standard Penetration Test (MSPT);
5.) using air photographs;
6.) using multispectral or hyperspectral scanners from aircraft or satellites.

3.1 Estimating Cone Index from soil groups and soil water content

Soils found on beaches and foreshores are divided by Jenkins (1985) into four groups which, in order of decreasing trafficability, are:

I: coarse grained gravelly and sandy soils;
II: highly plastic clays, also called heavy or fat clays;
III: clayey gravels and sands, and clays of low to medium plasticity;
IV: lean clays and silts which may or may not contain small quantities of gravel[2].

The first of these is the most suitable for landing and is typically found on the foreshores and backshores of beaches subject to large waves. Soils of type II are common on nearshore regions of beaches near river deltas, where there are low wave conditions. Type III soils are found on the nearshore regions of tidal lagoons and estuaries fed by seasonal river flows. Type IV soils are most typical of beaches formed along the banks of rivers that have little or no exposure to waves. They are the least suitable for landings. Jenkins (1985) provides ranges of CI and RCI for each of these soil groups when they are saturated with water and these are presented in Table 1. He then provides a table of soil strengths as a percentage of the saturated strengths over a range of soil water contents for each soil group. See Table 2. Note that soil properties over the top 150 to 300 mm are those of interest for vehicle trafficability estimations. The soil strengths obtained from this process are only approximate and provide a range of expected values.

[2] Gravel is defined as material with an average particle size between 2 and 60 mm, sand as between 0.06 and 2 mm, silt as between 0.002 and 0.06 mm, and clay as less than 0.002 mm. Lean clay is another name for an inorganic clay of low to medium plasticity.

Table 1. Cone Index and Rating Cone Index Ranges as a Function of Beach Composition when Wet.

Group	Soils	Probable Cone Index Range	Probable Remoulding Index Range	Probable Rating Cone Index Range
I	Coarse-Grained cohesionless sands and gravels	80 – 300	1	80 – 300
II	Inorganic clays of high plasticity, fat clays	65 – 165	0.75 – 1.35	65 – 140
III	Clayey gravels, gravel-sand-clay mixtures, clayey sands, sand-clay mixtures, gravelly clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays	95 – 175	0.45 – 0.75	45 – 125
IV	Silty gravels, gravel-sand-silt mixtures, silty sands, sand-silt mixtures, inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity, inorganic silts, micaceous or diatomaceous fine sands or silty soils, elastic[3] silts, organic silts and organic silty clays of low plasticity, organic clays of medium to high plasticity	85 - 190	0.25 – 0.85	25 - 120

Table 2. Percentage of Saturated Wet Strength as a Function of Moisture Content

	Water Content Within the 150 to 300 mm layer (mm)	Saturated Wet Strength (%) Soil Group		
		I	II	III & IV
DRY	35.6	46	112	621
	35.6	46	111	621
	38.1	40	111	463
	40.6	26	109	352
	41.9	46	108	274
	43.2	50	105	208
	44.5	77	100	163
	45.7	91	100	126
SATURATED	47.0	100	100	100
	48.3	95	85	81
	49.5	87	77	65
	50.8	61	62	53
FLUIDIZED	52.1	47	56	42

[3] Elastic silt is another name for an inorganic silt, or for a micaceous or diatomaceous fine sandy or silty soil.

3.2 Estimating Cone Index from Grain Size and Beach Slope

Jenkins (1985) provides the following regression equation for calculating CI values for saturated samples given field values for average grain size and beach slope:

$$CI = \frac{2\sin(\Phi - B)}{\tan\Phi(1+\cos\Phi)}\left[(10240)D + \frac{0.0024}{D^2} - \frac{0.158}{D}\right], \text{ if } D \geq 10^{-1}\text{ mm}$$

$$= \frac{\sin(\Phi - B)}{\tan\Phi(1+\cos\Phi)}\left[\frac{0.0376\times10^{-6}}{0.6D^3}\right]^{\frac{5}{2}}, \text{ if } D < 10^{-1}\text{ mm},$$

where D = average grain size in inches,
Φ = sediment's internal angle of friction = 30° to 34°,
B = beach slope.
If the beach slope is not known B can be set to zero, in order to estimate CI.

The obtained CI values must then be adjusted to obtain RCI values using soil group values for RI and the effects of soil moisture, discussed in section 3.1. The estimates of the effects of soil moisture can still be in error by 50%, so that one only obtains ballpark figures.

3.3 Estimating Cone Index from Surf Observations

Assuming an equilibrium beach profile, the smallest grain size appearing under the wave breakpoint is that which is just moved by the highest breaking wave. The threshold drag velocity under the highest breaking wave can be calculated from wave height and period, and water depth at the break point. The threshold drag velocity is related to grain size and from the grain size the CI value can be calculated as in section 3.2. Because beaches are not always in equilibrium the underlying assumptions used in this method can be inapplicable so that inaccurate results would then be obtained.

3.4 Using the Divers Miniature Standard Penetration Test (MSPT)

The MSPT is illustrated in Figure 2. It consists of a shaft with a cone tip at the bottom and a hammer with guide tube at the top. Following Jenkins (1985), the number of hammer-blows per 3 inches of penetration depth can be related to soil groups I to IV, listed in section 3.1. CI and RCI values can then be estimated as described in that section.

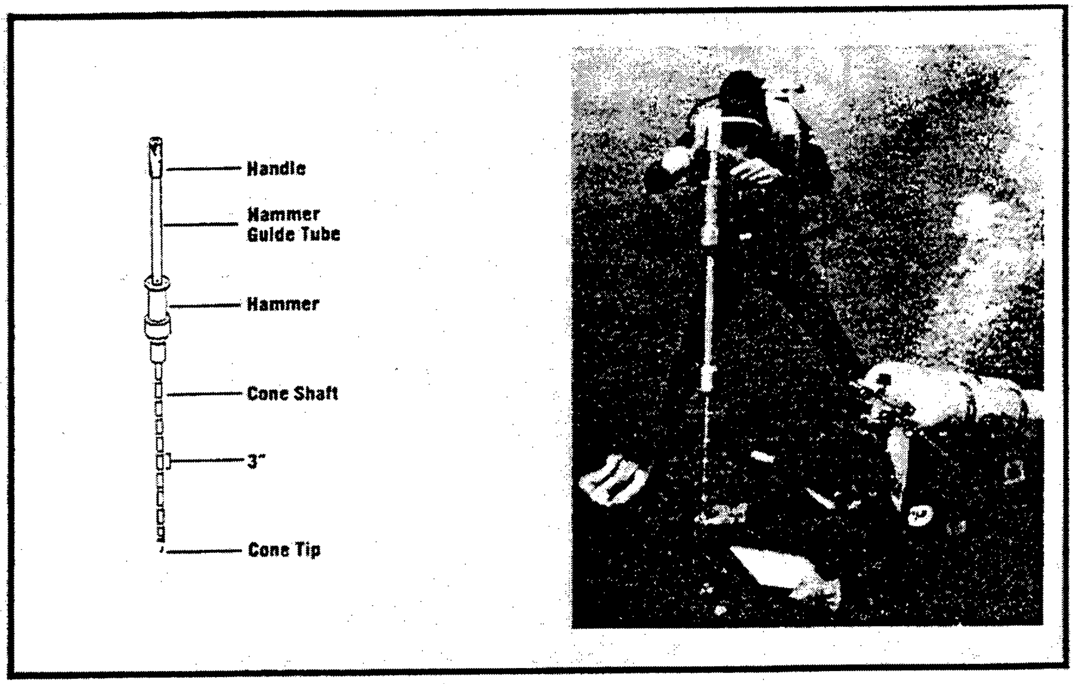

Figure 2. Miniature Standard Penetration Test (MSPT) device (from Johnson, 1986).

3.5 Using Aerial Photographs

This method was used during World War II. The estimates obtained are only qualitative due to scatter in observational results. Estimates of beach slope and foreshore width can be obtained from aerial photographs, given tidal data for the beach being surveyed. Crude correlations exist between median beach grain size and beach slope and foreshore width. From the estimates of grain size and beach slope CI and RCI can be estimated as in section 3.2.

3.6 Using Multispectral Scanners & Hyperspectral Scanners from Aircraft or Satellite.

Multispectral Scanners (MSS) are optical instruments which observe the earth's surface through a number of spectral bands (4 to 20) in the visible to thermal infrared range. Hyperspectral instruments provide information in many (30 or more) contiguous, narrow spectral bands in the visible to short-wave infrared range. Multispectral and hyperspectral scanners can be flown on either aircraft or satellites. Research has been carried out to determine grain size and soil moisture using airborne multispectral scanners (Kasischke, 1980; Shuckman and Rea, 1981). It was discovered that the reflectance spectra of beach sediments are dominated by their mineralogy. However if the mineralogy of a beach's sediment is known and its reflectance spectrum is available, moisture content and grain size can be estimated, using regression equations

previously obtained for that mineralogy. Shuckman and Rea (1981) did this with reasonable success for five USA mineralogical types, using a 17 band MSS. In general the mineralogy of beaches is not well known, let alone reflectance spectra. With modern hyperspectral scanners it may be possible to develop robust algorithms for separating out mineralogy, grain size and moisture content, but this would require much more research.

4. Conclusions

The most reliable method for determining beach strength is to use a cone penetrometer and the best of these appears to be the one developed by Stoll and others at Columbia University (Stoll et al., 1989). If such a direct method is not possible, less accurate (but still useful estimates) can be obtained by other methods. Of these the best is to use regression formulae between CI and grain size and beach slope. The remaining methods are really more qualitative but can be a useful guide.

5. Acknowledgments

The gathering of information for this report was helped by discussions with Mr Terry Duell of the Army Technology & Engineering Agency and e-mail correspondence with Dr Herbert Herrmann and Dr David Thompson of the Naval Facilities Engineering Center, Port Hueneme, California, and with Dr Dale Bibee of Naval Research Laboratory, Stennis Space Center.

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DOCUMENT CONTROL DATA

1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE Methods of Obtaining Soil Strength Data for Modelling Vehicle Trafficability on Beaches	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)
4. AUTHOR(S) P.J. Mulhearn	5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory 506 Lorimer St Fishermans Bend Victoria 3207 Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-GD-0299	AR-012-010	General Document	September 2001

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
490/6/89	NAV 98/025	COMAUSNAVAMPH IBASGRP	10	11

13. URL on the World Wide	14. RELEASE AUTHORITY
http://www.dsto.defence.gov.au/corporate/reports/DSTO-GD-0299.pdf	Chief, Maritime Operations Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

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16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS

amphibious operations, beach heads, beaches, sand, soil mechanics, bearing strength, field tests, soil tests

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GENERAL DOCUMENT DSTO-GD-0299 AR-012-010 SEPTEMBER 2001

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