Some Uncertainties in Embankment Dam Engineering[1]

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Abstract: In the design and construction of embankment dams, our current capability for precise mathematical analysis and modeling of induced stresses and deformations, or of potential seepage patterns, far exceeds our capability to make judgments of comparable accuracy concerning, for example, the site and geology or how the soil properties may be affected by the weather or by the contractor's methods. In addition, there is often a lack of adequate communication between the design and the supervision of construction. These uncertainties or doubts about the actual performance of the dam when constructed are discussed in the paper and illustrated by case history examples, with particular reference to the uncertain effects of cold weather, to the use of broadly graded soils (tills) as core and to problems in the placement, and segregation of tills and filter materials.

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Introduction

Terzaghi's contribution to geotechnical engineering was unparalleled. As stated by Casagrande in his Terzaghi Lecture (Casagrande 1965), Terzaghi's great accomplishment was to replace the large conglomeration of ''unknown risks'' in earthwork and foundation engineering by rational analyses based on the principles of soil mechanics that he developed and, in part, by ''calculated risks'' estimated with the help of these principles and by practical judgment.

Casagrande, in his paper, discussed the meaning and the role of calculated risk in foundation and earthwork engineering illustrating his discussion by case history examples. His paper, together with the contributed discussions, is still pertinent today and required reading for all geotechnical engineers. He proposed that the term ''calculated risk'' be used to cover the use of imperfect knowledge, guided by judgment and experience, to estimate the probable range of the pertinent soil properties and other parameters such that a decision can be made on an appropriate design solution commensurate with safety and economy. In his definition of ''calculated risk,'' he includes risks due to unknown factors, which he terms ''unknown risks,'' and uncertainties introduced by human failings, which he terms ''human risks.''

Casagrande listed some of the calculated risks in applied soil mechanics where he claimed ''--- we still depend largely on crude empirical knowledge and judgement because quantitative analyses are either non-existent or of very doubtful validity'' (1965). His list included risks associated with liquefaction, shear strength and the stress-deformation characteristics of plastic clays, and of coarse granular materials.

The human risks, referred to by Casagrande (1965) largely relate to the division of responsibility between the design and the supervision of construction; poor communication, or the lack of it, between design and construction exacerbates the situation. This is still a major concern today. Human causes have been stated by Sowers (1993) as being responsible for the majority of civil engineering failures. Ignorance or rejection of contemporary technology by the engineers involved were cited as the major cause; this certainly applies to embankment dam engineering.

This paper endeavours to complement Casagrande's theme by examining some of the risks in current construction practice as they apply to the design and performance of earth and rock fill embankment dams. In this respect, I have used the term ''uncertainties'' to describe the issues involved.

Concerning the Term ''Uncertainties''

The essence of the word ''uncertain'' is one of doubt and is defined in most dictionaries as ''*not having certain knowledge or assured conviction*.''

Today, there is still uncertainty in our ability to make precise judgments concerning almost all of the risks discussed by Casagrande. In the design of embankment dams, our capability for mathematical analysis and modeling of induced stresses and deformations, or of potential seepage patterns, exceeds our capability to control construction and account for variations in the site conditions, different from those assumed in the mathematical modeling. For example, the selection of appropriate filters and the prediction of their long-term behavior, particularly at the filter/core interface, are still based largely on empirical data and the judgment of the engineer. There is still a lack of certain knowledge not just about these issues, but also about other matters such as the details of the geology and site conditions; the as-placed properties of the fill materials, which are locally available; and, on occasion, a lack of agreement on the most appropriate placement method to obtain these properties with reasonable assurance.

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Another typical uncertainty, which is sometimes ignored, concerns the effects of variable weather conditions on construction and uncertainty regarding the effects of weather conditions on the constructed product. It is regrettable that, in cases, site testing and supervision of construction are entrusted to technicians or engineers of limited experience and who have not been associated with the design. There are also some regrettable instances of designers apparently unaware of accepted good construction practice.

All of these deficiencies of certain knowledge and associated doubts about the design and construction, including its supervision, I consider to be ‘‘uncertainties.’’ That they exist does not imply that they necessarily constitute a fatal flaw to safe design and performance, but it does mean allowance must be made for them in design and recognition of the fact that, despite remarkable advances in analytical techniques, a precise prediction of the performance of the dam is often a chimera and, at best, uncertain.

Obviously other engineers, based on their experience, have other uncertainties to add to those discussed in this paper and, equally obviously, the number of such uncertainties is too large to discuss in any one paper. Many of them have previously been examined [for example, Peck (1980)]. This paper discusses some of the uncertainties encountered either during construction or following the impoundment of embankment dams and includes

- Uncertain effects of cold weather,
- Use of coarse broadly graded soils (tills) as core, and
- Placement and segregation of tills and filter materials.

The project examples described generally reflect the accepted design methods and procedures at the time of their construction. Those concerned were not necessarily ignorant nor dismissive of the then contemporary technology, but in hindsight we may be critical of some of the decisions. It must be kept in mind that most retrospective analyses carried out at a later date are generally related only to specific technical issues and rarely, if ever, take into account the attitudes that often exist on a site because of pressures exerted by the client and by peers to achieve speedy completion of construction. Such pressures may be caused by economic concerns, or arise from exigencies created by weather conditions or the like. In addition, the contractor’s interpretation of the specifications may differ from the design engineer’s intent and, in the interest of keeping projects on schedule (generally assumed to be a hallowed phrase!), modifications to the design or construction method are permitted that are later found to be detrimental to the design.

Treatment of Uncertain Effects of Cold Weather

Climate is a major factor in embankment dam construction. Frost and freezing weather, in particular, affect dam construction in a number of ways: (1) during borrow excavation and fill placement; (2) by its effect on the core after placement; and (3) by the effect of thawing on frozen foundations, such as permafrost.

Effects of Cold Weather on Construction

Few countries suffer the effects of cold weather more than Canada and particularly the eastern Canadian Shield region (Milligan and Ripley 2000). At Manicougan 3 (Dreville et al. 1970), an earthfill structure over 100 m high on the Manicougan River, it was necessary to place glacial till core material in prevailing cold, rainy, short construction seasons. The till was nonplastic and wetter than the optimum water content and, to achieve reasonable placement conditions, the water content of some of the till borrow material was reduced by the use of a rotary kiln dryer. Light vibratory smooth-faced rollers were used to compact the till, producing a moist deformable core in situ, which has performed satisfactorily to date.

Uncertainty in obtaining a suitable core borrow material led to the dykes of the Outardes 2 hydroelectric scheme, adjacent to Manicougan 3, being constructed with an impervious core of local clay mixed with sand, which had been dried in a rotary kiln to develop a mixture at near optimum water content (Hammamji et al. 1982).

Hydroelectric development of the Nelson River in northern Manitoba was complicated by the widespread presence of permafrost. Ice in the form of lenses or inclusions was conspicuous in lacustrine deposits on which the dykes would be built. Where encountered in glacial till it was difficult to detect because of the very dense nature of the till. The presence of ice in till makes its removal extremely difficult, necessitating drilling and blasting. When the materials are then exposed to summer temperatures they soften quickly leading to problems of handling and placement.

Where dykes were low, the frozen foundation soils were left in place. The uncertainty was the amount of settlement that could take place as reservoir impoundment induced thawing of these underlying soils and the possibility that differential settlements could cause cracking of the core. The lacustrine soils were ice-rich in contrast to the underlying frozen dense tills and thus contributed most of the induced thaw settlements, for which the dykes were designed. An example of the design and construction of the dyke fills is the Kelsey project in Manitoba completed in 1960 (MacDonald 1963). Sand drains were installed in the foundation to improve stability during thawing and the dykes were built largely of sand in order to accommodate differential settlements. Experience gained in this project provided guidelines for subsequent work at Kettle Rapids in 1969 (MacPherson et al. 1970) and Long Spruce in 1977.

Not all tills are equally affected by frost. The broadly graded silty tills on the Labrador Plateau exist at low density, probably as a result of their method of deposition. These loose tills, combined with high groundwater conditions and a cold wet construction season are difficult to handle leading to uncertainty in determining their as-placed strength. Problems of instability of these tills were encountered during the construction of the Churchill Falls, Labrador, hydroelectric project in 1969–1970, causing costly disruption to normal construction operations (Seemel and Colwell 1976). Frost penetrations of over 5 m were encountered.

Another example of induced construction difficulties is given by the Snare Rapids hydroelectric development on the Snare River about 150 km north-west of Yellowknife. Construction began in 1946 and was completed in 1948. The dam, of modest size about 17 m high, is a zoned earthfill embankment with thick quarried granite-gneiss shells and built on permafrost, estimated to be in excess of 100 m thick. The only locally available core material was a uniformly graded fine silt (‘‘rock flour’’). Except for the upper 15 cm, this material was permanently frozen and could only be excavated in Spring by bulldozers peeling the surface as it thawed. The excavated material was stockpiled with the hope that some drying would take place. This expectation proved to be fruitless and it quickly became necessary to cast the semi-liquid silt onto the embankment with draglines and clamshells within shoulders of clean sand, which fortuitously was locally available in large quantities. The rockfill shells were raised in keeping with the core placement. Some cracking of the crest oc-

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curred several years following impoundment, but after being filled with sand, have never reappeared. Despite great initial uncertainty about the performance of the dam, recent inspections indicate continuing satisfactory performance, even after almost five decades of use.

Effects of Freezing of Core Following Construction

Solymar and Nunn (1982) discuss the problems associated with freezing of the embankment dam core following placement. This is particularly important in northern Canada where the choice of material suitable for use as impervious fill is extremely limited and winter conditions are harsh. In addition, many, if not all, of the locally available borrow materials are frost susceptible—some to a marked degree. There is thus considerable uncertainty concerning the behavior of the fill when subjected to very cold temperatures.

Frost penetration into the core is dependent on a number of factors such as the freezing index (degree-days below freezing) at the site and the amount and type of cover, or frost insulation, provided to the core. Random variations in the snow cover, for example, which often cannot be predicted, can have a marked influence on the depth of frost penetration (Duguid et al. 1973).

Most embankments in Canada, which have suffered frost damage following construction, appear to have relatively narrow crest widths and steep side slopes. With side slopes steeper than 2(H) to 1(V) local instability has occurred during summer thaw periods resulting in longitudinal cracks developing along the crests; often silt boils are observed in the upper slopes and along the crest. Solymar and Nunn (1982) recommend flatter slopes and wider crests be adopted wherever possible; providing an increased thickness of protective fill to restrict frost penetration into a frost susceptible core material obviously involves increased fill volume and dam height, but this strategy must be treated with some caution as it has been found that clean dry sand and gravel often provides little benefit as an insulator compared to other means of insulation.

The remedial work carried out at Waterloo Dam in northern Saskatchewan (Noonan et al. 1982) gives an interesting example of core insulation. This 19 m high embankment was built in 1961 on discontinuous permafrost with a core of uniformly graded silt, the only suitable material available. The dam behaved well during initial impoundment, but with time the permafrost in the left abutment thawed inducing some leakage and minor slope sloughing. These were repaired. However, over the next two decades, annual severe winter freezing caused ice lenses to form repeatedly in the upper downstream portion of the silt core leading to silt boils on the downstream slope and longitudinal cracking along the crest. The situation was eventually solved by partial excavation and replacement of the core together with the provision of styrofoam insulation to the upper part of the central section of the embankment. Performance has been excellent since repair.

An interesting example of the effects of frost even in a relatively mild climate is provided by Kelso Dam. This is a 15 m high earth fill embankment about 800 m long with its axis running in a generally east-west direction and located in Southern Ontario. It is one of several embankments built in the 1960s in the local area to form conservation and recreational lakes.

The embankment is a homogeneous section with upstream and downstream slopes, 2.5(H) to 1(V), of glacial till, a broadly graded material of low plasticity ranging from cobble sizes down to rock flour, with a simple toe drain typical of such homogeneous sections. The dam is founded on till generally of the same char-

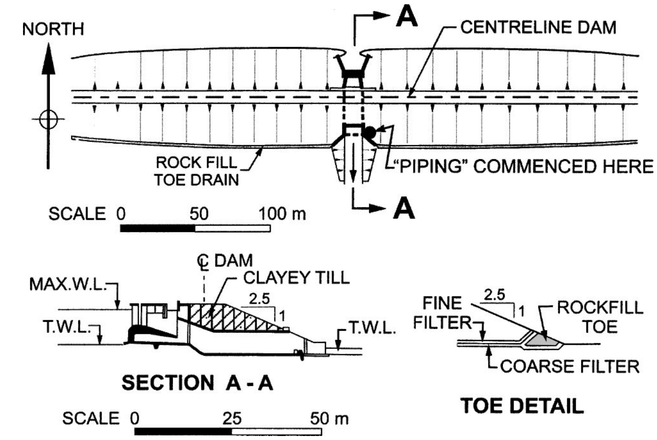

Fig. 1. Kelso Dam plan and sections

acter as that used for the embankment fill. Lake levels are controlled by a gated reinforced concrete box-bottom outlet constructed at about the midlength of the embankment. A plan and typical section of the dam are shown in Fig. 1.

Following construction of the dam, the lake level was raised in early Spring to over half of full height and maintained there for about 2 years. Some seepage was observed at the toe of the dam adjacent to the east side of the outlet structure, but the quantity was modest. At the end of the summer season, the level of the lake, which was relatively small, was lowered almost completely to permit maintenance of the gate structure. Impounding did not then take place until late in the following Spring. This impounding was relatively rapid and, as it took place, seepage markedly increased in the same place as before at the toe of the dam such that, as the lake level approached full height, local erosion at the toe became extreme and a ''pipe'' of almost a meter in diameter on the downstream face rapidly developed despite the outlet having been opened. Fortunately, flooding damage in the recreational area downstream was not extensive.

Detailed examination and investigation of the area of embankment adjacent to the side of the outlet structure showed that a ''piping tunnel'' had developed along the east side of the concrete structure and, gradually reducing to much smaller size, extended through the embankment to the upstream face. Thin patches of ice were evident on some parts of the exposed concrete face and the till material, where still present within about a meter of the wall, was wet, ranging in water content from about 20% to as high as 40%, the average water content being about 25%. This is in contrast to the water content of the fill material elsewhere in the embankment; for example, the average water content of the fill about 3 m distant from the east wall was about 15%, which was about equal to the original placement water content. These data are illustrated in Fig. 2.

It is obvious that the fill material adjacent to the east wall of the outlet had been frozen. The fill elsewhere and even adjacent to the other side of the outlet structure exhibited no signs of having been frozen. This freezing occurred during the winter when the lake was empty. That winter had been extremely cold and the prevailing wind was from the northwest. Since the axis of the conduit is north-south, it acted, in a sense, as a wind tunnel with the east face of the concrete structure being exposed to freezing winds for a considerable period. As a result, the frost susceptible till adjacent to the exposed concrete wall became frozen and it is most likely that ice lenses developed in the till. With the onset of

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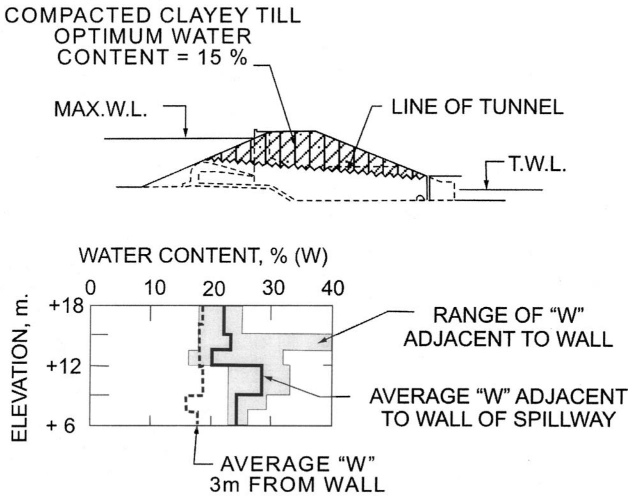

Fig. 2. Water content of frozen core material

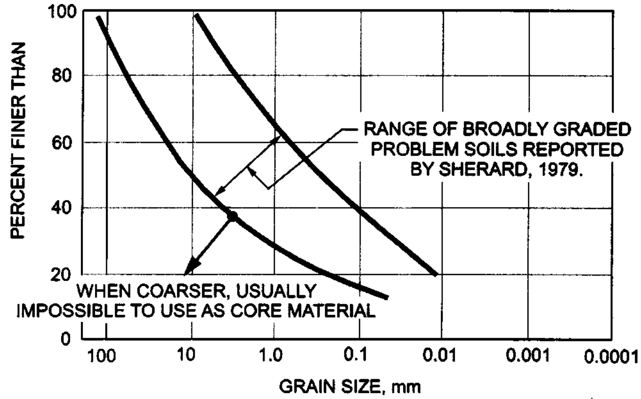

Fig. 3. Broadly graded problem soils [after Sherard (1979)]

warmer weather and then impounding, thawing of the ice lenses and of the frozen material led to seepage and subsequent erosion and piping.

The embankment section adjacent to the east side of the outlet was reconstructed. A concrete stub wall encasing a partial sheet pile cut off was constructed at the centerline of the dam and extended about 6 m from the wall of the outlet structure along the dam axis. Upstream of this cut off, selected till, which was more plastic than that previously used, was placed to extend about 3 m from the wall; downstream of the cut off, a sand filter was placed against the stub wall and extended to the downstream toe. The original till material, compacted at optimum water content, or slightly above, was replaced elsewhere. The behavior of the embankment since reconstruction and impounding several decades ago has been excellent despite occasional partial drawdown of the pond level.

There have been many cases of seepage problems associated with conduits passing through dam fills, particularly in freezing climates. In this case, an additional uncertainty was the unforseen occurrence of severe winter conditions coinciding with maintenance and drawdown of the lake.

Use of Coarse Grained, Broadly Graded Soils (Tills) as Core

The risk of using coarse, broadly graded soils as cores has been examined in a thought-provoking paper by Sherard (1979). He discussed a number of seepage incidents in dams and concluded that soils within the typical gradation illustrated in Fig. 3 are internally unstable, because the fine portion is not compatible with the coarser particles from the standpoint of filter requirements. He considered this instability to be the principal cause of sinkholes that have appeared, sometimes several years after initial impoundment, in the crest of well constructed modern embankment dams where relatively thin, central, nonplastic cores (generally glacial tills) were used. In all the examples cited by Sherard, a single broadly graded downstream filter was provided adjacent to shells of rock fill or gravel; in most of the examples, the foundation bedrock below or against the core was jointed.

The characteristic feature of these glacial tills is that they are reasonably similar in gradation throughout the world, but the character of the fines content depends on the source rock. For example, in Canada the source rocks in much of the western Prairie provinces are sedimentary and the fines can be of high plasticity: in eastern Canada, where the source rocks are igneous or metamorphic, the fines in these tills are either nonplastic (rock flours) or have relatively low plasticity. Most of the incidents, not exclusively, apparently occur in tills of lower plasticity and follow a similar pattern. A leak develops near the base of the core and the finest soil particles are carried away passing through the broadly graded filter into adjacent coarse fill, or into joints in the foundation rock. The remaining "washed" core material is then incapable of preventing progressive erosion of fines over the full height of the core and sinkholes at the crest of the dam then result.

It should be recognized that such glacial tills have been used for the cores of a number of successful embankment dams over many years (Milligan 1976; Pepler and MacKenzie 1976). The reported incidents represent only a very small percentage of the total number of such successful dams and in no case did complete failure result. In many of the cases examined by Sherard, the leakages appeared to diminish with time, even if no remedial action was taken; in some cases, high leakages only occurred intermittently during periods of high reservoir water levels, as at Suorva Dam (Bronner et al. 1988). Thus, it has been inferred that some degree of "self healing" can take place. Such healing might be the result of the clogging of voids eroded in the downstream part of the till core by fines transported from the upstream parts of the core, or as suggested by Dascal (1984) and as discussed by Peck (1990), is the result of "the upstream face of the filter (being) sealed by eroded core material carried by the concentrated leak." Thus, in these cases, the core/filter interface then provides the effective water stop in many dams. However, it is not possible to verify these hypotheses absolutely, nor can we accept, as a basis for design, that such will inevitably occur. As Peck (1990) suggests "defense in depth--- should remain a guiding principle for all designers of dams."

Sherard (1979) states that there are few examples of sinkholes developing in embankment dams with cores of other materials. However, a notable exception to this is the case reported by Taylor (1963) where extensive erosion of the plastic clay core and adjacent thin sand filter into the downstream rock fill shell resulted from intense seepage from open joints in the limestone foundation. Only prompt drawdown of the pumped storage pond saved the 17 m high dyke from complete collapse.

There is no doubt that a properly graded filter, appropriate to the gradation of the finer portion of the broadly graded material,

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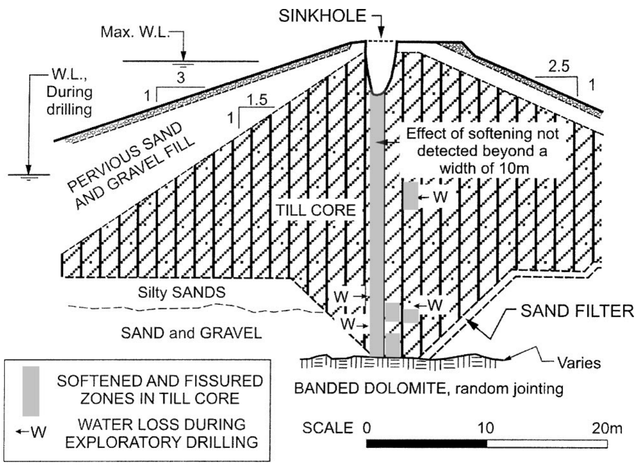

Fig. 4. Conestogo Dam: cross section

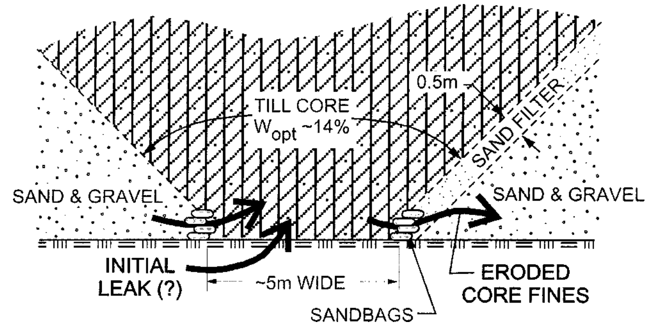

Fig. 5. Core trench detail

as suggested by Sherard, would have prevented most, if not all, of these incidents. As pointed out by Ripley (1984), there have been no incidents of adverse seepage in any embankment dams, even with cores of till, where a sand-rich downstream filter of adequate dimensions has been used.

As stated by Leps (1979) in his discussion to Sherard's paper, one can completely agree that the need for treating and sealing the bedrock under and adjacent to the core is essential, but not necessarily with the claim that ''broadly graded coarse soils are internally unstable.'' Many tills, except when badly gap-graded, are highly stable to seepage in situ, but are difficult to excavate and place as fill without segregation resulting. The uncertainty is therefore not just related to the range of gradation as postulated, but to the specific character of the till matrix when placed as core material. This issue, and the attendant issues of foundation treatment and of a suitable filter, are discussed in the examples that follow.

Conestogo Dam is an embankment dam some 30 m in height built as a conservation structure several decades ago on the Grand River in Southern Ontario, Canada. It is a relatively homogeneous section, largely of low plasticity till, and rests on some 5 m of broadly graded sand and sandy gravel river deposits overlying dolomitic limestone.

Shortly after impoundment, a local depressed area and cavity developed in the crest at about the mid point of the embankment. This was filled in and over the next 2 years further settlement took place, the rate of settlement apparently increasing as the reservoir was drawn down. No unusual seepage or seepage losses downstream were observed at any time, but a hole then developed in the asphalt road surface at this location. Further investigation showed that a sinkhole about 1 m in diameter and 1.5 m deep existed. Investigatory cased boreholes, using wash boring methods to advance the holes, also indicated that there was a localized zone of disturbed and softened core material throughout the full depth of the embankment. Occasional fissures were encountered and at depth within the core, wash water flowed freely into the fill, the loss of water continuing until bedrock was penetrated. However equilibrium water levels in the holes were invariably at reservoir level. There were no indications of any significant connection to the tailwater downstream and the embankment was not in any danger. A summary of the conditions as observed is illustrated in Fig. 4.

The most likely cause of the softening and erosion of the core leading to the development of the sinkhole arises from the conditions during construction. Considerable difficulty was experienced in unwatering the core trench excavation. The excavation was locally widened and water pumped from perforated pipe drains in the existing sand and gravel deposits. Sand bags were used to retain the toe of the excavation in some places. [Traces of these sand bags were found in one of the exploratory borings on the upstream side of the core trench (Fig. 5)]. In hindsight, it seems likely that pervious zones connecting directly to the reservoir existed in the upstream part of the foundation. Through gaps between sand bags, these zones could impinge directly on the unprotected core within the trench and could have led to an initial leak causing local softening and erosion of fines into coarser zones of the downstream gravel deposits.

The defect / uncertainty in this case appears to be related to the doubtful nature of the foundation treatment and limitations in the provision of a downstream filter rather than solely to any inherent instability of the core material. In many cases of dams with a cut-off trench beneath the core, the hydraulic gradient across the core is greatest in the cut off. Design measures to prevent migration of core particles in this region are particularly important. For example, where the cut-off trench is within rock, shotcreting of the sides and base of the trench is a necessary measure, together with ensuring that the downstream filter extends to the base of the core.

Remedial grouting of this part of the core and of the bedrock directly underlying was carried out. The dam has since performed well for several decades without any signs of further erosion.

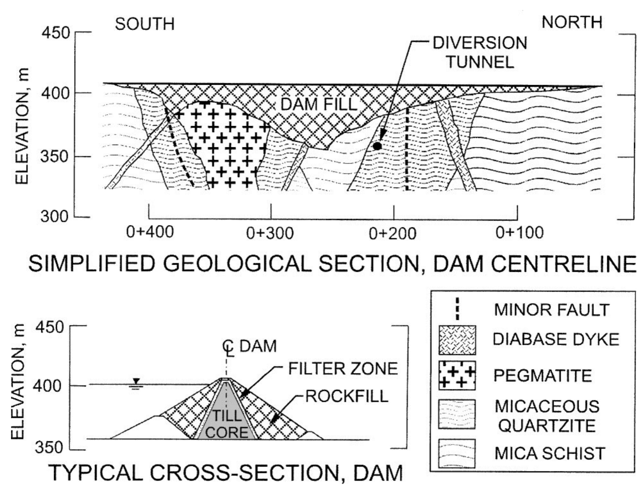

Fig. 6. Incident 1—Site geological section (looking upstream)

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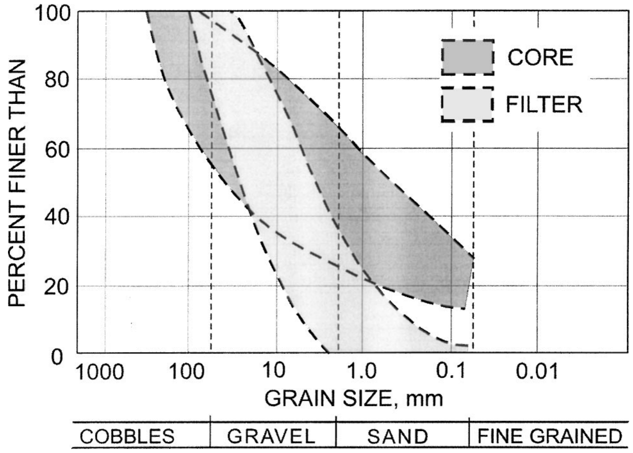

Fig. 7. Incident 1—Core and filter gradations

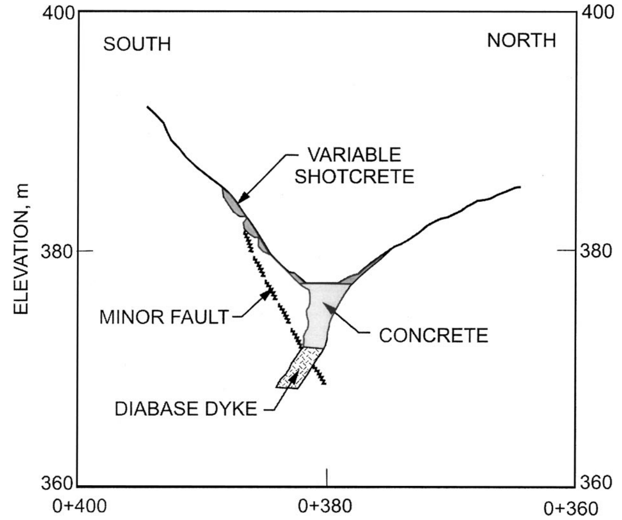

Fig. 8. Incident 1—Section through gulley (looking upstream)

The Wreck Cove hydroelectric project, located on the Atlantic coast of Cape Breton Island, Canada, consists of some 12 embankment dams and reservoirs, which together with ancillary dykes, collect and divert water to a common reservoir feeding an underground powerhouse, which in turn, discharges into the sea. Most of the embankments, which range from about 17 to 50 m in height, have rock fill shells with a central core of glacial till founded on hard igneous rocks typical of the Pre-Cambrian shield; the lower dams have a homogeneous section formed of glacial till. The design cross section adopted is common to all the dams with rockfill shells and the gradation of the till used is remarkably consistent within the general range shown on Fig. 3. Thus this project, in itself, offers a good opportunity to assess the behavior of broadly graded till cores.

At most of the dams, seepage losses, where observed, were relatively minor and generally in keeping with design assumptions. At several dams, some local areas of depression were observed at the crest, but no sinkholes developed, but at two of the dams, significant leakage occurred during and following initial impounding: details of these incidents are discussed further.

Incident 1

This dam is a rock fill embankment about 50 m in height with side slopes of 1.5(H) to 1(V), a central till core and relatively thin (2 m), broadly graded, upstream and downstream filters. The rock fill was largely derived from excavations for an emergency spillway located adjacent to the south abutment.

A longitudinal section of the dam, looking upstream, and a simplified geologic section along the centerline are shown on Fig. 6. Core and filter gradations are given on Fig. 7. Blanket grouting to a depth of more than 6 m was carried out along the complete core/foundation contact area, but not up the abutments.

During construction, attention was given to the treatment of the foundation and to the placement of core and filter in a steep gully located high on the south abutment (Fig. 8). The weathered upper part of the diabase dyke was excavated and replaced with concrete, irregular rock faces were cleaned and scaled. Some shotcreting of exposed rock surfaces was also carried out, but the extent of this treatment was incomplete. Additional foundation grouting was carried out to treat the minor fault zone that had been exposed during excavation. Because of concern about possible differential settlements in this section, the downstream filter was increased to over 4 m width.

During initial impoundment, when the reservoir level approached within about 4 m of the crest, seepage was observed at the toe of the downstream shell in the lower part of the gully referred to above (Fig. 9). The rate of seepage rose abruptly to about 200 L/s (6 cusecs). The water was relatively clean and contained little sediment. No seepage was evident elsewhere along the toe of the dam and seepage was apparently confined to this local area.

Possible explanations of this seepage, as shown on Fig. 10, were as follows:

- Horizontal cracking in the core caused by arching of the core fill across the gully;
- Seepage through joints in the foundation rock, possibly opened by blasting for the emergency spillway excavation, and connecting directly to the reservoir at a relatively high elevation; and
- Seepage at the core/foundation contact zone within the gully leading to fines being washed out from the core material, which were not retained by the coarsely graded downstream filter.

Steps were taken immediately to lower the reservoir level; as it lowered, the rate of seepage reduced correspondingly. Investigation of the condition of the core and of the core/foundation contact zone in the gully area was commenced using hollow stem

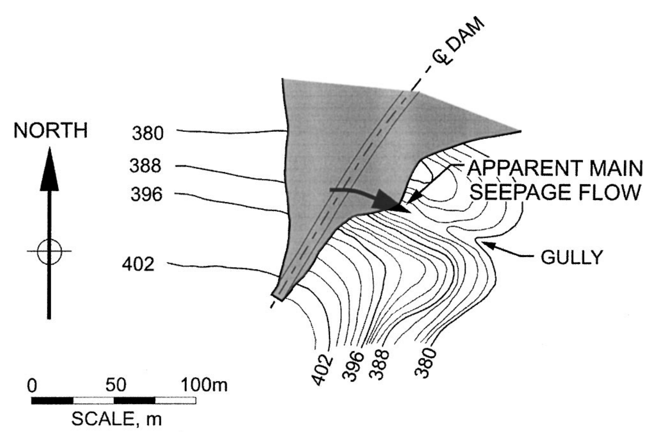

Fig. 9. Incident 1—Plan of south abutment

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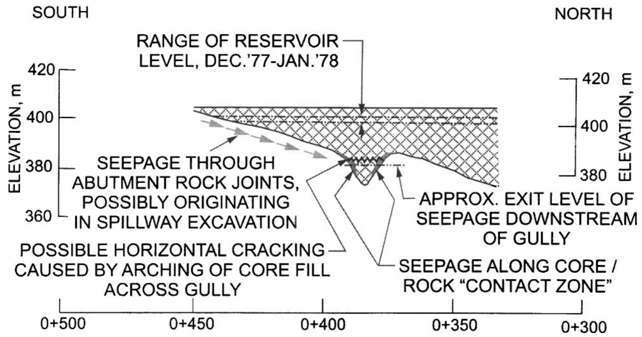

Fig. 10. Incident 1—Possible explanations of seepage

augers to penetrate the core, drilling from crest level. (This method was adopted in order to avoid possible hydraulic fracture, which might be induced by wash boring methods.) The borings indicated the core to be intact throughout its depth except for soft zones close to the contact with the underlying foundation in several borings located on the south side of the gully area. Other borings taken into rock in the same area indicated significant water takes within about 10 m of rock surface. Low-pressure cement grouting was then carried out in rock over about a 100 m length, extending from the gully to the south abutment; holes within the dam fill were backfilled with sand/cement/bentonite grout under gravity head. The effectiveness of the grouting is demonstrated in Fig. 11; the reservoir level was then raised to full height with no further incidents of seepage.

The fact that seepage did not take place elsewhere in the dam, even where water pressures were substantially greater, strongly suggests that the irregular profile of the gully, the difficulties in treating the rock foundation and in placing the core material in this area are probably the primary causes of the seepage. It is likely that because of inadequate treatment of the foundation, open joints in the rock, possibly affected by blasting for the adjacent emergency spillway channel, could expose parts of the till core to high hydraulic gradients and leading to erosion of the till in some places.

A synthesis of the grout takes recorded in lines of grout holes located respectively along the centerline, 1.5 m upstream and downstream of the centerline, is plotted on Fig. 12. While these grout takes are relatively modest, it is interesting to note that grout takes in the rock consistently increased in a downstream direction, probably reflecting the heavily jointed character of the rock adjacent to the gully. It should also be noted that the significant large takes of grout backfill within the core, under gravity

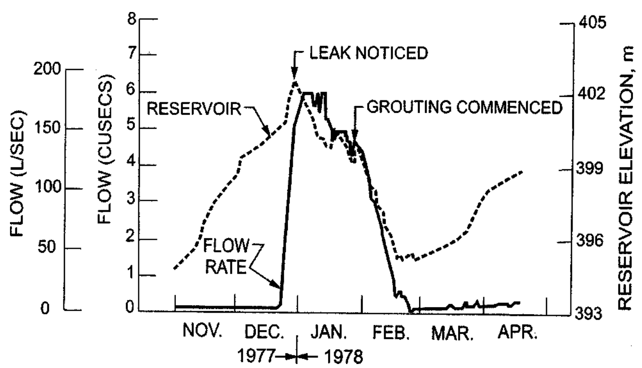

Fig. 11. Incident 1—Observed seepage flow rates

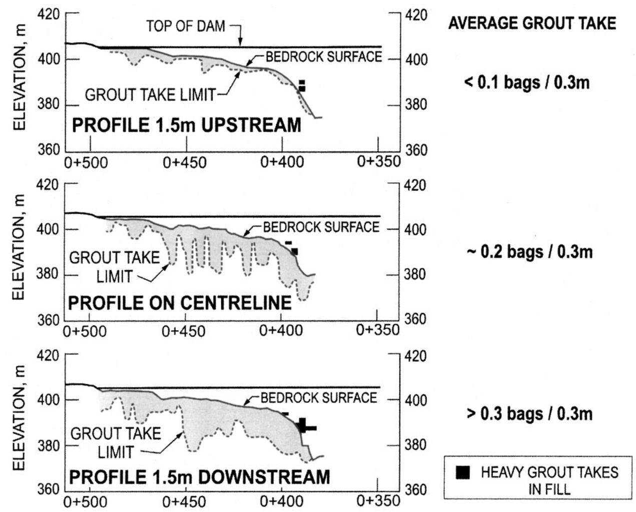

Fig. 12. Incident 1—Details of remedial grouting

pressures only, occurred only on the south side of the gully, providing a further indication of the deficiencies in the core/rock contact in this local area.

This incident has certain parallels with that reported at Suorva Dam (Bronner et al. 1988) and suggests that the uncertainties associated with the use of the till as core stem largely from the inadequate treatment of the irregular rock foundation in the gully area, from difficulties in placement of the core against the foundation and in ensuring a satisfactory core/foundation contact with appropriate defensive measures. The subject of core/foundation contact is examined further in the following section on placement and segregation.

Incident 2

The second incident occurred near the end of the project in the area of the power pool, which was formed by raising the water level in an existing irregular rock depression, known as Surge Lake, through the construction of two low dams. These rockfill embankments, about 18 m high, one being about 200 m and the other 450 m in length, were similar in design to that discussed above, except that, to accommodate the need for repeated drawdown of power pool levels, the upstream slope was flattened to 1.75(H) to 1(V). The geology and embankment materials were similar to those previously described; grouting of the rock foundation below the embankments was minimal.

About 2 months following initial impoundment, minor seepage was observed in a local area at the downstream toe of the longer dyke (Fig. 13). This quickly increased to over 15 L/s, the water becoming cloudy. More importantly, a small sinkhole developed at the upstream edge of the crest, followed the next day by a similar sinkhole at the downstream edge of the crest. The reservoir was then drawn down and it was decided to carry out additional grouting of the foundation from the crest of the dam and partially remove the downstream shell and filter to permit inspection and possible replacement of the filter and shell in this area. During the initial progress of this work, jamming of the diversion tunnel gate occurred and the water level rose rapidly overnight causing increased "dirty" water seepage at several locations in the general area of the previous seepage. The concentration of flow in one location caused severe erosion of exposed

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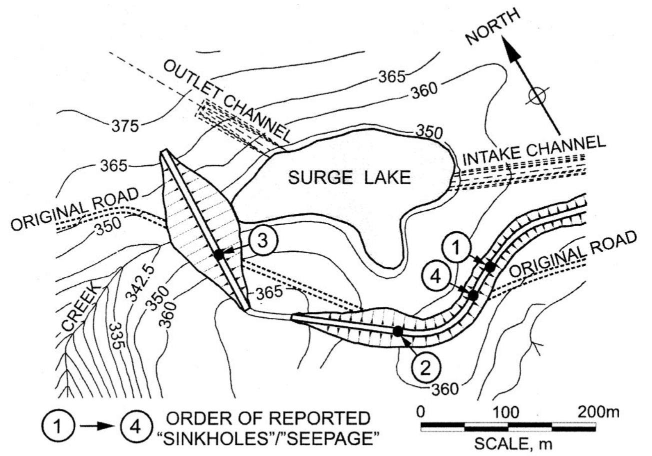

Fig. 13. Incident 2—Site plan

filter material locally remaining on the steep downstream slope of the core material. The total seepage rate was estimated to be about 250 L/s or more.

Excavation and stripping of the remaining downstream filter at this location revealed a clearly defined hole in the core, about 30 cm in diameter, dipping strongly downwards and that apparently extended for some distance into the core. Complete removal of this section of the embankment was then commenced by excavation of the upstream rockfill shell and filter. This disclosed a similar hole in the core at about the same elevation and extending slightly downwards for some distance into the core. While further construction activities did not permit an absolute definition of complete continuity between the upstream and downstream holes, there was sufficient other evidence to indicate that they formed a single path through the core, as illustrated in Fig. 14.

This section of the embankment was completely removed and the exposed foundation rock in the core trench, which was weathered and fractured, was excavated by backhoe for about a meter, then grouted to a depth of over 10 m. Grout absorption in the rock was extremely low (corresponding to cement takes of less than 0.05 bags/30 cm); additional water testing confirmed the extreme tightness of the foundation. The embankment was reconstructed with a slightly wider downstream filter than before using the same materials, and the water level raised.

Over the next several months of operation following this local reconstruction, sinkholes of a similar pattern to those initially observed developed in the crest at other locations as illustrated in Fig. 13. Seepage losses at each of the locations were relatively small, of the order of 25 L/s, or less, but the water was invariably

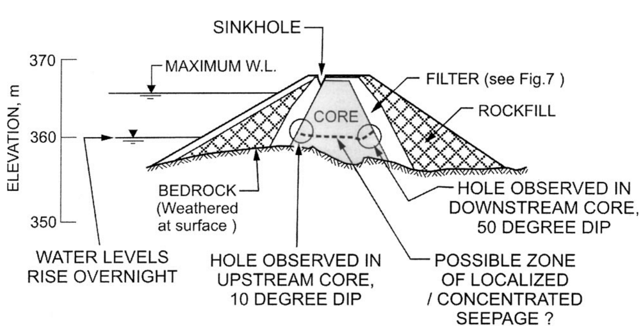

Fig. 14. Incident 2—Cross section showing locations of ''piping''

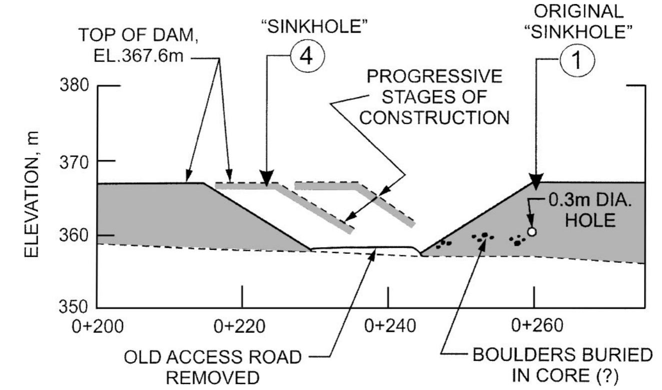

Fig. 15. Incident 2—Illustration of filling gaps across access road

dirty. The pond level was again drawn down and an investigation shaft was excavated through one of the sinkholes at the contact between the filter and core. In the lower part of the shaft, extensive ''washing'' of the core and filter was evident in some zones close to foundation level such that only large size cobbles and coarse gravel remained.

Because of the relative tightness of the foundation at the location of the first incident, the seepage and sinkholes there seem to be related to causes other than the condition of the rock; however at the other locations, the foundation rock was observed to be jointed and fractured and this could have led to the later sinkholes. An initial leak could have developed through open joints in the untreated rock in the foundation near the downstream edge of the core; water would then flow upwards washing the fines in the core into and through the coarse downstream filter. In the first incident, a lack of compaction or improper placement in some layers of the till core material above the foundation could have created random loose pervious zones, which led to the subsequent piping at the elevation shown.

Whether or not these hypotheses are wholly correct, there is no doubt that in all the incidents, the gradation of the filter material adjacent to parts of the core was too coarse to prevent washing out of the finer sizes from the broadly graded till and a two-stage filter of substantial thickness incorporating a more suitable ''sand rich'' material adjacent to the core would have been preferable. However, it may be equally significant to note that the route of the access road, as shown on Fig. 13, and that was maintained during construction, appears to be remarkably coincident with the location of all of the subsequent sinkholes. In fact, during excavation for the reconstruction of the embankment following the first seepage incident, a section of culvert pipe from this road was found at the edge of the rock fill. An illustration of the pattern of gaps left in the embankment during construction, and of the probable method on infilling of the embankment material in these gaps, is shown in Fig. 15. This pattern of construction raises several questions:

- Was all road bed material excavated such that the foundation below it was cleaned, washed and treated comparably to other sections of the embankment?
- Were the edges of the road bed partially covered with spilled till material from the sloping core ramping upwards on both sides of the road?
- Did cobble sizes and segregated till material tend to accumulate along the lower part of the ramps during subsequent filling of gaps?

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All of these questions relate to the issue of satisfactory placement and compaction of the core material and of the broadly graded filter material. Most broadly graded materials cannot practicably be placed without some segregation taking place. This leads to the creation of random streaks or layers of segregated soil fines within the fill, which may be progressively eroded by heavy seepage flows; these streaks can be of substantial horizontal extent and can well be adjacent to streaks of coarse gravel in the filter, sufficiently coarse to permit loss of the washed fines into the rock fill. In this case, it is known that some of the till core and filter material was placed on an inclined surface (sloping ramp), which would have greatly exacerbated the problem of segregation during construction. While it is recognized that a ''good'' filter will limit the amount of fines, which can be lost from the core by erosion, this beneficial effect cannot be wholly relied on if the integrity of the core is questionable, or if the filter itself is badly placed. Prevention of the segregation of both core and filter materials is vital to ensuring the integrity of the dam.

Since the initial remedial measures were completed, there were several further incidents, including recurrence of the initial leak. These have necessitated treatment, but there have been no further significant incidents for over a decade. However, the satisfactory behavior of the other embankments on this project, all of which are similar, cannot be assumed to be completely fortuitous and suggests that uncertainties arising from the placement and segregation of coarse graded tills and of the filter may be much more significant than the intrinsic ''internal stability'' of such materials.

Placement and Segregation of Tills and Filter Materials

Placement of Tills

The issue of segregation is a critical uncertainty that is generally poorly recognized and dealt with even more poorly in construction specifications. It is dealt with on many projects by the simple declarative statement in the specifications that ''materials must be placed without any segregation taking place.'' All broadly graded materials are difficult to place without segregation; indeed, all materials that do not have sufficient fines to provide some degree of cohesion, tend to segregate. Thus, in many cases, the specification places an obligation on the contractor that cannot be met. For example, because of segregation, it is almost impossible to obtain a satisfactory contact between a broadly graded till core and a rock foundation or abutment, however it may be prepared. Coarse sizes, including cobbles, tend to accumulate at the contact zone. To prevent this occurrence, the designer should specify that a practicable thickness of a finer grained and more plastic core material be placed against rock faces, or equivalent rigid boundaries; if such material is not locally available, the available till should be processed to eliminate the coarser fraction and the remaining finer material compacted against the rock surface.

Design of Filters

Practical rules for the design of filters were first proposed by Terzaghi (1922) and reported in 1925. As Ripley (1988) has pointed out, the general acceptance of these criteria and recognition in the 1940s of the dangers of piping and internal erosion led to the increasing use of filters. However, for several decades, commencing in the 1950s and 1960s, there was a trend from the use of uniformly graded multiple filters to the use of a single filter of substantial width and broad gradation based on the belief that a broad gradation in itself, would ensure self-healing and that segregation was not a problem. Regrettably this belief was often applied indiscriminately and the use of multiple zones of graded filters became largely neglected.

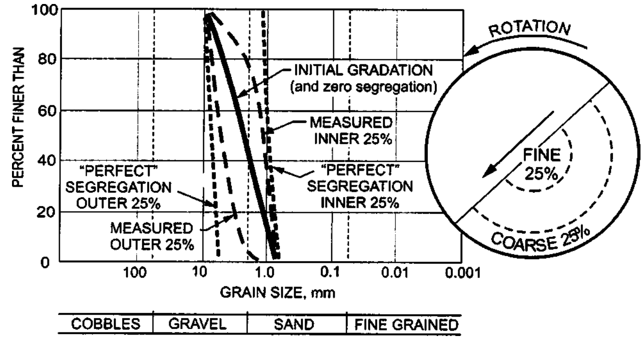

Fig. 16. Relative segregation index

The essential requirement of a filter is to provide appropriate void sizes, which will seal sufficiently to prevent concentrated leaks. A number of examples of embankment dams where significant erosion took place and core materials were piped into and through single broadly graded downstream filters have been reported in the literature, typical of these being by Vaughan et al. (1970), Vestad (1976), Wood et al. (1976) and Ripley (1984). To meet this requirement, the work of Vaughan and Soares (1982), Sherard et al. (1984), Kenney et al. (1985) has been particularly significant in establishing suitable criteria. It is now generally accepted that good filters should be sand rich, with a maximum size less than about 75 mm and a maximum D_{15} size less than 0.7 mm, and in some cases less than 0.5 mm.

More recently, Foster and Fell (2001) have presented a comprehensive assessment of embankment dam filters that do not satisfy currently accepted design criteria. One of their conclusions was that dams with good filter performance have filters with characteristics that would tend to make them less susceptible to segregation. This is most significant and is discussed further below.

Placement and Segregation of Filter Materials

Uncertainty always exists in ensuring that filters and transition materials are placed satisfactorily without leaving segregated zones of sufficient coarseness, which would permit loss of fines from the core. It has been pointed out by Milligan (1986) in discussion to the paper by Kenney and Lau (1985), which examines the internal stability of granular filters that the gradations of the ''unstable'' materials tested tend to be typical of materials which segregate readily. In relation to this problem, the later work on the segregation of cohesionless soils carried out by Kenney and Westland (1993) is extremely relevant and provides an approximate method of quantifying their potential for segregation. Tests were carried out in the laboratory using a large rotating drum to induce segregation of a variety of relatively coarse granular materials. By sampling the inner and outer zones of the material after testing (each zone representing 25% of the total volume), they assessed the degree of segregation by defining a Relative Segregation Index (RSI), as illustrated in Fig. 16. If the outer zone corresponded in gradation to the coarsest portion of the initial sample and the inner zone to the finest portion, then this would represent perfect, or complete, segregation with a corresponding RSI of 1.0. If the initial gradation remained unchanged

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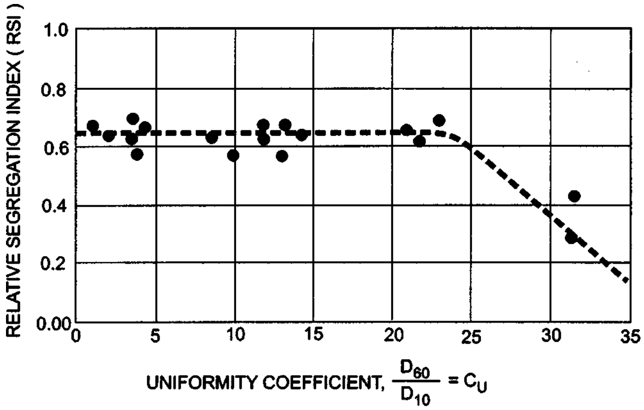

Fig. 17. Influence of the degree of uniformity on segregation

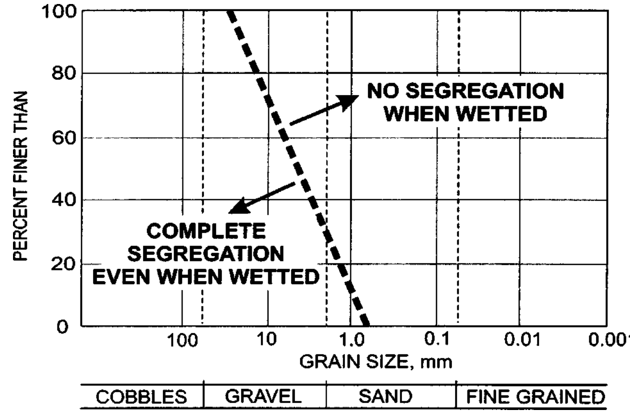

Fig. 18. Approximate gradations limit to the effect of wetting in preventing segregation

in both zones, which would be the case if there were no segregation, then RSI would be zero. For results between these two extremes, the RSI can be expressed in relative proportion to the bounded areas illustrated on the grain size curve.

It was found that all the cohesionless soils tested, over a wide range of gradation, tended to segregate about the same amount *relative to their* original *gradation* with a corresponding RSI value of about 0.7. This result is particularly significant in relation to the placement of filter materials. Even for the uniform sand and gravel shown in Fig. 16, the D_{15} size of the material, when segregated, could possibly range from about 0.9 to 3 mm. While we must recognize that the rotating drum test produces an extreme degree of segregation, which probably exceeds that which usually occurs in engineering practice, this range is excessive if a maximum D_{15} value of 1.0 mm has been assumed for design. In itself, this is a strong argument against the use of broadly graded filters. However, if the filter has a gradation corresponding to that of a concrete sand, a potential RSI of 0.7 gives a possible range of D_{15} size from about 0.2 to 0.7 mm, which is acceptable for the protection of almost all soils.

While some degree of segregation of *dry* cohesionless coarse materials can thus be assumed to be almost unavoidable, an increased content of sand sizes markedly inhibits segregation *provided that* the material is wetted prior to placement. The apparent reduction of RSI when the uniformity coefficient ($C_u = D_{60}/D_{10}$) exceeds about 25, as noted in Fig. 17, is the result of increasing fines (<0.06 mm sizes) in the *dry* material tested. If the more sandy materials are *wetted*, segregation is almost completely inhibited; in contrast, water has little influence on the segregation behavior of gravels. A very approximate gradation limit to the effect of wetting in preventing segregation is indicated in Fig. 18 (Milligan 1999). It is of some interest to note that this limit corresponds approximately with the coarsest filter gradation proposed by Sherard in 1985 as a means of inhibiting segregation.

It is widely accepted that, in addition to controlling the filter D_{15} size, a low value of C_u is highly desirable. However, as pointed out by Kenney and Westland (1993), the coefficient of uniformity is only of limited usefulness and should only be used with caution as it does not account for particle sizes larger than D_{60}. These sizes are those most likely to separate out and thus lead to problems. It is essential therefore that the maximum particle size be restricted. Ripley (1986) recommends that the maximum filter size be restricted to 18 mm, that at least 60% of the particles be finer than 5 mm, but no more than about 2% be finer than 0.08 mm. This gradation also falls within the limit proposed in Fig. 18.

The work on segregation by Kenney and Westland (1993) has now been extended by Sutherland (2002) through a detailed examination of the various mechanisms of segregation, conducting laboratory tests that would better model the process of field placement of granular materials and reassessing the potential for coarse zones to be created by segregation, particularly in filter materials. Sutherland's work has demonstrated that most, if not all, of the problem filter gradations reported in the literature are materials that can be classified by his proposed method as highly susceptible to segregation. Typical results are illustrated in Fig. 19 and complement the suggested coarse limit shown in Fig. 18.

It can thus be concluded that much of the uncertainty related to appropriate filter design and placement may be largely resolved by specifying the use of wide, narrowly graded, sand-rich filters, of a gradation finer than the limit suggested in Fig. 18, and placed wet in thin lifts. Then the specification clause that "segregation will not be permitted" is a practical reality.

Influence of Excessive Fines

However, the prevention of segregation *per se* does not resolve all of the concerns about placement and performance of the filter. The necessary requirements of a filter and the core/filter interface as pointed out that by Peck (1990), are that even if the core cracks (and this is a prudent assumption), the downstream interface becomes, in effect, a secondary core element. An essential feature is therefore that the filter material, as placed in the dam, will not itself be fine enough to hold a crack. If both the core and filter can

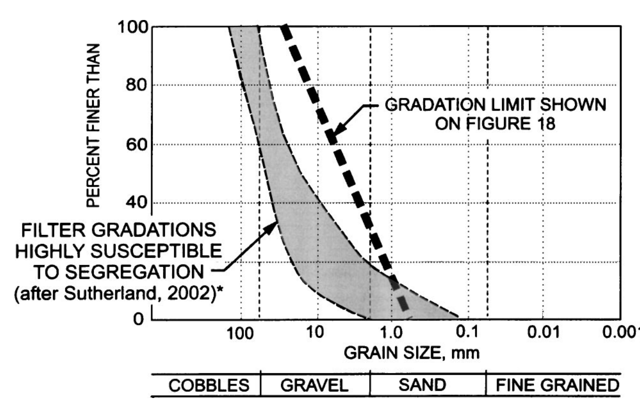

Fig. 19. Filter gradations highly susceptible to segregation

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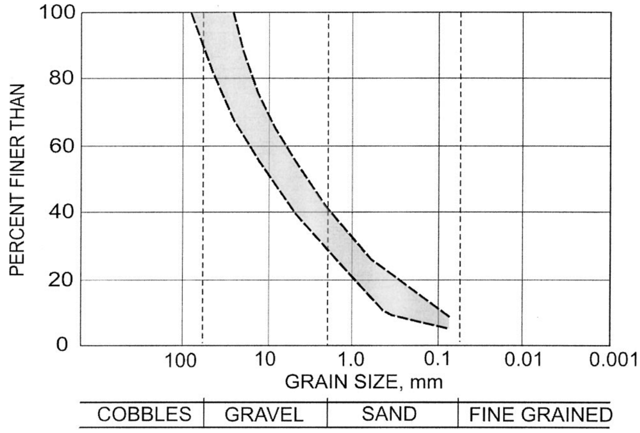

Fig. 20. Specified filter gradation (Peru)

sustain open cracks, erosion and piping will result. To prevent this, the filter should therefore collapse when wetted.

A simple but effective test to check the potential collapsibility of compacted filter materials has been proposed by Vaughan and Soares (1982). A sample of the compacted material is taken from a split mold, placed in a basin, which is then slowly filled with water; as the water level rises, any capillarity in the sample is destroyed and the sample collapses. This laboratory test procedure has been used by the writer to examine the behavior of wetted filter samples used on a number of dams, which were then checked by observing their behavior in test pits dug into the same material when placed in the embankment. Occasionally, as the test pits were filled with water, the walls in some pits did not collapse as expected, but quickly filled with water and remained flooded for some time, ranging from minutes to hours; after the water level fell, the pit slopes were still intact. This result was surprising in that the laboratory samples had exhibited satisfactory collapse. Sampling of the material in the embankment invariably disclosed a high relative density in situ and a higher fines content than that specified. It was apparent that the material, as originally processed, differed from the material, after placement. This can arise if the contractor is permitted to use the filter zone as an occasional haul road. Core borrow material may then be spilled on the filter zone and the combined effect of traffic and of spillage from haul trucks can produce a rigid fill mass markedly different from the design intent.

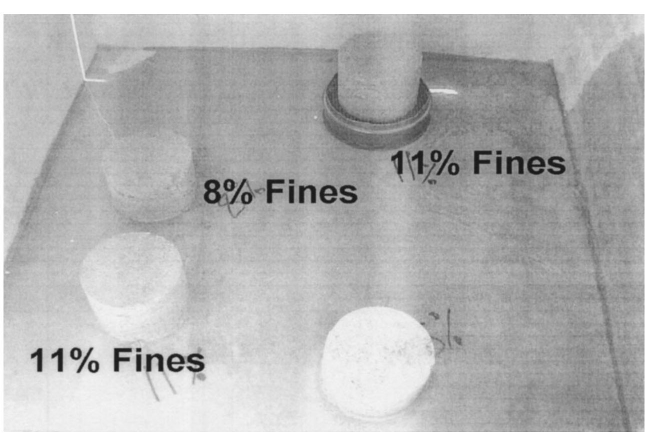

Fig. 21. Compacted filter samples—not flooded

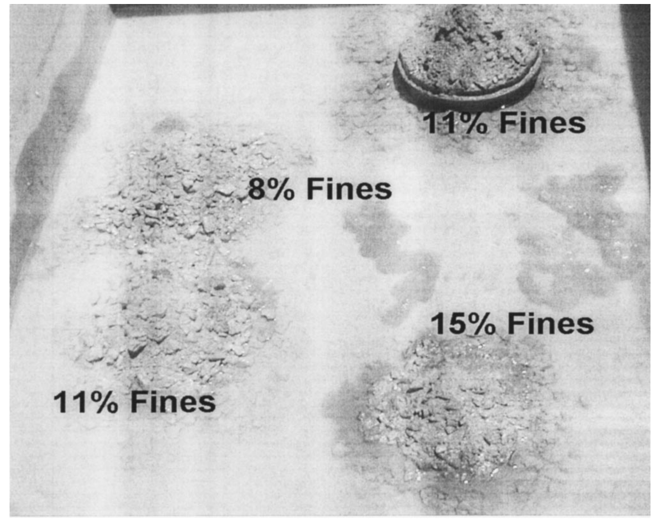

Fig. 22. Compacted filter samples—after flooding

Even where traffic over the filter zone is carefully controlled, the effect of truck hauling to the site and consequent compaction may lead to some breakdown of particle sizes and thus a detrimental increase in fines content. This is particularly the case where filters are derived by processing of quarried hard rock. An example of this effect was observed in the recent construction of an embankment dam in Peru. The rock fill dam proposed was to be about 200 m in height; it would be located in a highly active seismic zone; relatively large deformations could be anticipated on first filling and possibly subsequently. It was considered to be essential that the filter materials be ample in width and also be unable to sustain a crack. Local river deposits were not available and the filter material had to be obtained from crushed hornfels some distance from the site. The filter gradation initially proposed is shown in Fig. 20. Satisfactory collapse tests were carried out on laboratory samples, even where the fines content exceeded the specified maximum of 8% (Figs. 21 and 22). However, flooding of material meeting the specified gradation, when placed and compacted in a test fill, clearly indicated no corresponding collapse of the pit sides (Fig. 23); however, the behavior of another test pit, excavated to form a cylinder of compacted material, indicated some collapse (Fig. 24). Sampling of the fill material indicated a higher fines content in situ than that of the originally

Fig. 23. Test pit (a) in filter—after flooding

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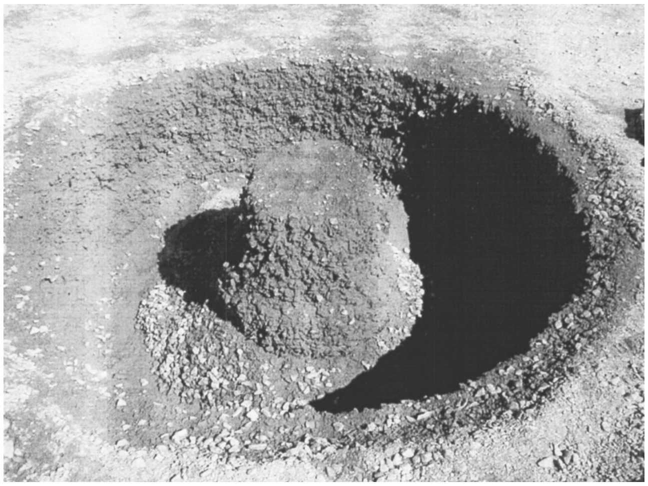

Fig. 24. Test pit (b) in filter—after flooding

processed material. The increase in fines was the result of particle crushing and breakdown caused principally by the effects of placement, handling and compaction of the material on site.

Cracking of Filters

Unacceptably rigid filters, which could hold a crack, have also been observed as a result of the heavy compaction of filters derived from other hard rocks, such as crushed massive limestones. The effect has rarely, if ever, been reported for filters derived from natural sand and gravel deposits. These natural deposits are of subrounded or rounded particles that are the product of repetitive particle breakdown, abrasion, and deposition over geological time. Thus, they do not contain any structural weaknesses (micro cracks) that have not already failed. On the other hand, man-made crushed filter particles have experienced severe but short-term damage and would be expected to contain structural weaknesses as well as sharp edges. Stressing of these man-made particles during compaction and loading causes further particle breakage resulting in increasing the fines content. We are still uncertain concerning what range of particle sizes can lead to dense, brittle materials when compacted, or concerning what processes are involved in making a compacted granular material behave as one that is cohesive, stiff, and hence brittle. What types of crushed rock should be avoided? With this degree of current uncertainty, the preferable recourse is to use natural materials for downstream filters and upstream crack stoppers, wherever possible.

An additional concern is that, in most embankments, the filter zone, as placed, whether of natural or man-made materials tends to be rigid in comparison to the core adjacent to it. Recognizing the importance of the core/filter interface, the filter and core should be relatively compatible in behavior, thus in most cases, the need for compaction of filters may be largely overstated. Placement methods currently employed are usually sufficient in themselves to produce an acceptable relative density.

It is considered that our present uncertainties concerning filters can only be addressed by recognizing that it is not enough to specify filter gradation and check its performance in the laboratory, but we must also specify the method of placement and means of checking its performance as placed on site.

Closing Remarks

This paper discusses some of the uncertainties in the design and construction of embankment dams. Examples, from the writer's experience, of some practical factors that are largely related to currently accepted construction practices, illustrate how marked differences from the design intent may arise.

The most significant of the uncertainties discussed in the paper are as follows:

- In cold climates, freezing of poorly insulated core materials can occur and subsequent thawing of ice lenses in the core lead to piping;
- Internal erosion (piping) of broadly graded till core materials may result more often as a consequence of segregation during placement rather than from presumed inherent ''hydraulic instability'' of tills;
- Because of the potential of broadly graded tills to segregate during placement, it is recommended that they should not be placed against concrete walls or rock surfaces;
- All dry granular materials tend to segregate during placement. Means of assessing and reducing such segregation are discussed;
- The use of single, widely graded one-stage filters should be avoided; multistage, narrowly graded filters are recommended;
- A uniform sand, with a maximum size not exceeding 30 mm and a D_{15} size less than 0.7 mm, is recommended as the preferable downstream filter for most core materials, provided it is wetted during placement in order to inhibit segregation;
- Filters should be tested for desirable collapse on wetting by laboratory tests during the design stage and by field tests during construction; and
- Compaction of filters should be minimal. Excessive compaction, particularly of crushed rock, can lead to the creation of sufficient fines in the filter to make them susceptible to cracking.

The importance of concern about uncertainties has been best expressed by Wallace Chadwick in his discussion to Casagrande's paper ''because civil engineering usually deals with natural conditions and forces, definitive design data are not available, with the result that many times judgement and experience must be relied on in design instead of such data, with proof possible only from full-scale trial.'' This is particularly applicable to embankment dam engineering.

It is postulated that uncertainties are an unavoidable feature of embankment dam engineering; however provided they are recognized, steps can be taken so that they do not lead to damaging risk. Undoubtedly there are other and possibly more important uncertainties than those discussed. It is hoped that this paper will provoke and stimulate discussion of these.

Acknowledgments

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