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HYDRAULIC FILL STRUCTURES

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CONSTRUCTION METHOD FOR IMPROVING UNDERWATER SAND FILLS

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ABSTRACT: A novel construction method is suggested for improving the engineering characteristics of underwater sand fills. The idea of pumping water out of submerged sand fills concurrently with fill placement, in order to generate inward seepage flows through the sand mass, is presented as a possible means of producing higher densities, steeper side slopes and enhanced erosion resistance. Two separate model test programs designed to investigate this method are described in detail. The second series carried out at the Hydraulics laboratories of the National Research Council of Canada was undertaken to verify the initial test series performed in Ireland. It is concluded that this method achieves the desired affects under laboratory conditions and at the model scale used. A working hypothesis is offered as a basis for further research into the forces which effect sand deposition underwater. A reason for the very flat slopes typically observed under field conditions is also suggested.

INTRODUCTION

Dredged sand is frequently used as a material for constructing underwater earthfills. A noteworthy example of this is in the recent offshore hydrocarbon searches in the Arctic waters of the Beaufort Sea in North America. These exploration programs have in most cases been conducted from man-made surface piercing islands constructed using dredged sand, or from mobile drilling platforms ballasted down on top of submerged sand fill berms.

In many cases sand is used because it is the only readily available granular material close to the site. Unfortunately, the ready availability and relatively cheap cost of dredged sand is offset to a large extent by the poor engineering characteristics of the resulting sand fills. As well as being poor compared with gravel or rockfill, the properties of underwater sand fill cannot be predicted at the design stage. One does not know what sort of strength and deformation characteristics will be attained until the fill is in place, after which time these parameters can be estimated from insitu testing. In other words, a typical dredged sand fill is not an engineered earthfill and you take what you get; consequently, it is not possible to optimize the design and minimize costs. This may be an acceptable situation for temporary islands or construction facilities in shallow waters, but it is not acceptable for permanent structural support or for situations where the sand fill may be subjected to significant static or dynamic loading.

Dredged sand, when placed through water, has three undesirable characteristics which compare unfavourably with coarser grained fills such as gravels or quarried rock:

i) Sand fills can be of variable density, containing large zones of very loose material.

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ii) Sand mounds normally have small side slope angles.
iii) Sand is easily eroded by currents or wave action.

Each of these characteristics has a serious impact on the acceptability of a sand fill mound placed conventionally through water:

a) Inadequate or unreliable packing density is generally the most serious disadvantage. Under static loading, low densities result in poor strength and deformation behaviour. A submerged sand fill is, however, rarely subjected to only purely static stresses. Natural causes such as wave action, earthquakes, and in the Arctic, drifting ice can induce dynamic stresses. Cyclic stresses imposed on submerged sand fills may be sufficient to cause liquefaction, or at lesser intensities, can lead to large deformations. Adequate density is necessary therefore, both in providing resistance to failure and in limiting the amount of structural movement.

b) Side slopes as flat as 3° to 5° are common in underwater sand fills. The volume of fill required to produce a given sized island or berm increases dramatically with flattening of side slopes. In the particular case of Arctic work, the sand volume required for conventional fills in deeper water may exceed the dredging capacity of the fleet working within the construction window which is dictated by the ice-free season. Flat slopes also have an environmental ramification, inasmuch as the larger the sand volume needed, the greater the extent of natural seabed disturbance, when both the area buried beneath the fill and the area removed at the borrow pit are included.

c) Erosion is not so much of a problem under current construction conditions where the sand fills normally end up at very flat slope angles. Erosion would become much more of a consideration if it proved possible to place sand at steeper side slopes.

The question addressed here is whether there is a simple practical method whereby a dredged sand dumped through water can be treated in such a manner as to produce a fill with acceptable engineering characteristics, which could be predetermined with some degree of reliability at the design stage. The purpose of the research work outlined in this paper was to attempt to assess one such method, i.e., pumping water out of the submerged sand fill during placement.

The research was carried out in several phases. Initially, the idea of dewatering during placement was checked out in rough fashion in the author's backyard using simple apparatus. These results were sufficiently encouraging to warrant more detailed work. In September 1983, the research was taken to University College Cork, Ireland, where suitable soil mechanics and hydraulics laboratory facilities were made available. The "Cork" testing gave qualititive, and to a limited degree, quantitative support to the broad concept. The Canadian Government was next approached with a request for financial assistance to do a field test. The National Research Council of Canada (NRC) insisted on larger scale verification testing in their Hydraulics laboratories in Ottawa prior to committing funds to a field trial. NRC also required that the verification testing be supervised by an independent geotechnical consulting firm. The author's company, Phoenix Engineering Ltd. (Phoenix), designed the test program and testing equipment for the "Ottawa" work, and engaged Golder Associates Ltd. to monitor the research. The NRC model testing commenced in August 1985. Following the Ottawa program, Phoenix set about the development of the field equipment necessary to build a prototype sand fill at an offshore site.

PUMPING WATER FROM SUBMERGED SAND FILLS

For the various reasons outlined above, the use of dredged sand placed underwater is currently limited to specific cases of fairly small temporary structures which are not sensitive to deformation. Despite its abundance and low unit placement cost, its use cannot be contemplated at present for such structures as earthdams, causeways or breakwaters because of its poor performance. The objective of the work reported here was to test a simple technique in the hope that it might provide a sand fill with characteristics similar to those of coarser grained fills.

Sand is composed of cohesionless discrete particles, but so too is quarried rock. They achieve roughly the same density when placed underwater, but the fill behaviours are significantly different. The difference is obviously associated with particle size. This may be stated in terms of specific surface where the smaller the grain size, the greater is the ratio of the surface (water) forces to the body (gravitational) forces. Or, phrased differently, the smaller the grain size, the greater will be the influence of viscous forces associated with water movements on the individual particles of sand. At the beginning of this study these drag forces or seepage forces were considered to be the likely root cause of the undesirable characteristics of submerged sand fills. For that reason, it was also believed that if seepage forces could have such a profound detrimental effect on submerged fills, then it was also possible that reversing the direction of the same seepage forces might have an equally powerful beneficial effect.

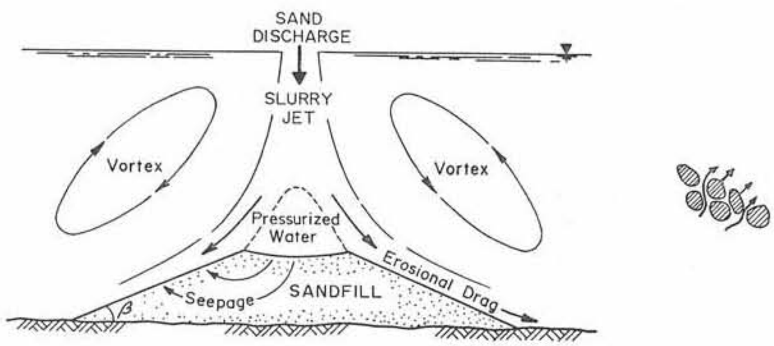
The destructive nature of pore pressure and seepage forces depends entirely upon the direction in which these forces act, i.e., from inside the body of the deposit outwardly. This perversive natural tendency towards outward seepage is due to the fact that pore pressure is normally generated within compressible saturated soil structures when the mass is subjected to increased loading. If, however, seepage forces could be made to act inwardly on a submerged fill they should have a beneficial effect comparable in influence to the detrimental effect of outwardly flowing water. This is conceptually easy to do - by withdrawing water from within the fill in order to lower the pore water pressure to a level below that of the outside ambient water pressure. Water would then flow into the submerged fill rather than flow out of the fill. The procedure of dewatering existing subaerial slopes to improve stability of open cuts has been, of course, standard practice for many years. But it has not been used underwater, presumably because it appears absurd to dewater an underwater fill. The novelty of the technique proposed here, however, is not simply related to providing a steeper slope in an existing deposit underwater; the novelty lies in attempting, during the fill placement operation itself, to cure all three of the behavioural problems of a sand fill in a single operation.

The hypothesis which evolved from this reasoning and which was subsequently tested in the research documented here may be stated as follows: The act of dumping dredged sand underwater introduces energy into the previously placed fill. This energy is converted into pore pressures within the sand mound. The outward gradient potential from the sand mass into the surrounding water results in outward seepage. These seepage forces decrease slope stability, decrease the packing density of surficial particles as they are being deposited and also lessen resistance to erosion on the face. Negating excess pore pressures and reversing the direction of the seepage forces while the fill is being placed would lead to steepening of side slopes, improve packing density and also the sand's resistance to erosion. Figure 1 depicts the general concept. A mathematical model was constructed for the forces acting on a surficial particle and this is summarized in the Appendix.

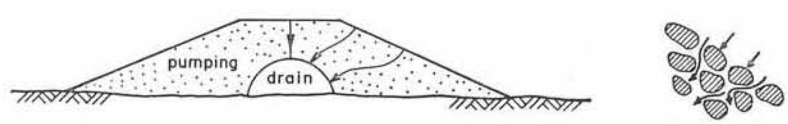
The essence of the concept was that the seepage forces must be made to act inwardly concurrently with sand placement. Slope steepness must be attained during construction; it is obviously not possible to pull up flat slopes after they are placed. Also, it is at the moment when a sand particle is falling out of suspension and coming to rest on the surface of the fill that its packing density can most readily be improved. A surface particle is not burdened by the weight of fill above it, and consequently seepage forces are more likely to be able to pull it into the spaces between adjacent particles at that moment. When a particle is buried it can only move into closer packing at the expense of generating additional pore pressures, and this movement can only be forced by applying external effort. Finally, because inward seepage forces increase effective normal stress on surficial grains it was believed that this would also increase their resistance to erosion. As will be discussed later, the laboratory and model testing programs reported here led to some contradictions of this mechanistic understanding and forced some rethinking of the general concept.

INITIAL LABORATORY TESTING (CORK)

The initial laboratory testing was carried out at Cork during October and November 1983. The testing program described below was designed to determine if the direction and magnitude of seepage forces prevailing during sand desposition underwater could be correlated with both side slope steepness



Destabilizing Water Forces Generated by Sand Placement.



Beneficial Inward Seepage Forces Generated by Pumping.

FIG.1.- CONCEPTUAL MODEL USED AS BASIS FOR INITIAL HYPOTHESIS

and with packing density. The sand selected for use in the Cork tests was a fine beach sand of the gradation shown on Figure 2. The grains were mainly subangular quartz with some shell fragments. The natural angle of repose of this sand in air was 33.7°.

Model Islands

This test series consisted of building small submerged sand fills inside a glass-sided water tank to determine, in a simple visual way, if seepage flows could be used to increase or decrease the steepness of side slopes underwater. The apparatus shown on Figure 3 was constructed for that purpose. A total of 16 models, about 200 mm diameter, were examined. Four of the tests were carried out by pouring dry sand directly into the water; a sand-water slurry was used in the remaining 12 tests.

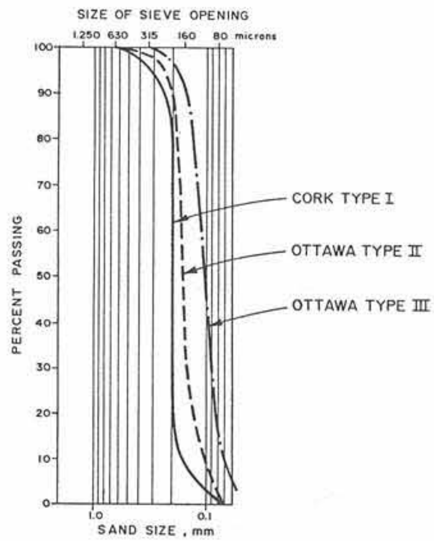


FIG.2.- GRADATION OF SANDS USED IN MODEL STUDIES

Prior to commencing sand placement, the base of the tank was covered with a layer of sand. A drainage element was embedded in this sand at the centre of the tank. The drain was dome shaped and was filtered against sand entry. The drain was connected by tubing to a back-pressure control vessel. By adjusting the water level at the brim of the back-pressure tank with respect to the water level within the modelling tank, a water pressure gradient could be exerted across the sand fill while it was being built.

The slurry was mixed by allowing dry sand to pour from a sand hopper into a small water reservoir. The slurry was siphoning into the modelling tank through a hose whose outlet was fixed in place just below water level at the centre of the tank. The slurry density and the rate of slurry discharge were controlled by the orifice size on the sand hopper, and by the difference in water levels between the mixing reservoir and the modelling tank. Four base line models were constructed without drainage, eight tests used inward seepage and four tests were subjected to outward seepage flows. In these latter tests only small incremental head differences could be exerted against the slopes without causing quicking of the top of the mound.

Figure 4 contains photographs of two sand fills which were formed with the aid of inward seepage flows. Figure 4a shows a mound built by discharging dry sand; the slope angle attained was 40°. Figure 4b shows a mound formed by a slurry discharge. The slurry imparted more energy to the water above the crown than did the dry sand; consequently, there was considerably more flattening of the upper sand surface as a result of the impinging jet. The asymmetrical shape of this particular model was caused by the jet being misaligned with the drain. The side slope closer to the drain is steeper (44°) than the far side slope (36°). This disparity is consistent with the hypothesis because the slope closer to the drain was subjected to a higher hydraulic gradient than the opposite slope.

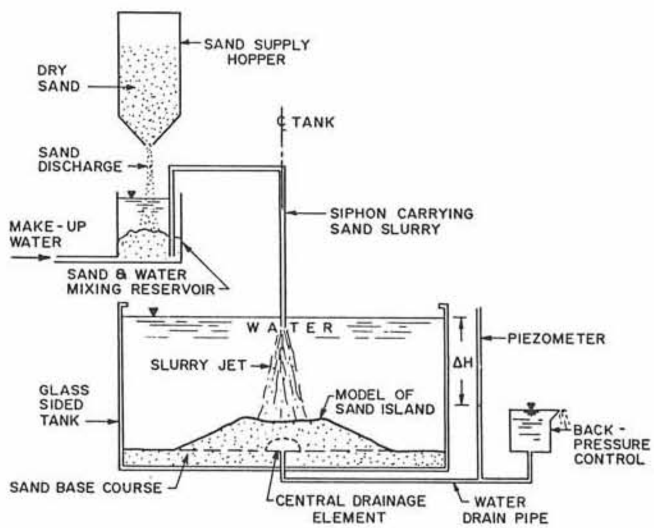


FIG.3.- MODEL ISLAND CONSTRUCTION APPARATUS USED AT CORK

In order to assess the results of the 16 tests on a comparative basis the plot shown in Figure 5 was made. Here, the side slope angles measured on the models are plotted against the ratio of the hydraulic head difference (H) across the sand fill and the radial distance (R) between the drain and the side slope. In a confined aquifer this ratio would be equivalent to hydraulic gradient, but due to the exposure of the top of the fills to open water, the actual gradient affecting the side slopes is less than indicated by the ratio of H/R. In this figure opposite slopes have been plotted separately. This data indicates a trend towards steeper side slopes with increasing magnitude of inward seepage. Flatter side slopes were measured when the direction of water flow through the sand was outwards. These test results appear to support the basic concept that side slope steepness could be modified during fill placement by imposing seepage forces on the growing mound.

(a) Mound Formed by Dry Sand Pluviation into Water Tank.

(b) Assymetrical Mound Formation when Slurry Discharge Misaligned with Drain.

FIG.4.- SELECTED PHOTOGRAPHS OF MODEL ISLANDS TAKEN DURING CORK TESTING

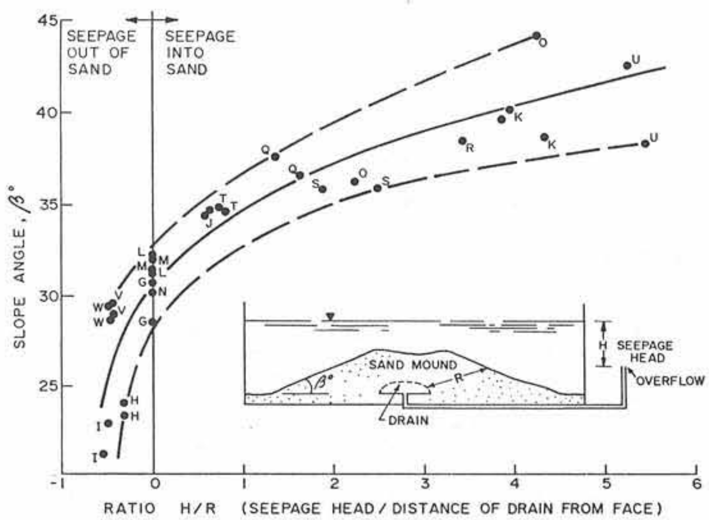


FIG.5.- RELATIONSHIP BETWEEN SLOPE ANGLE AND SEEPAGE BASED ON CORK MODEL ISLAND DATA

Density Tests

The apparatus shown schematically on Figure 6 was constructed in order to ascertain if the density of sand could be influenced by exerting seepage forces on the sand during the course of its deposition. Because seepage force per unit volume is directly proportional to hydraulic gradient, the test apparatus was designed so that the hydraulic gradient could be kept constant throughout each sand placement.

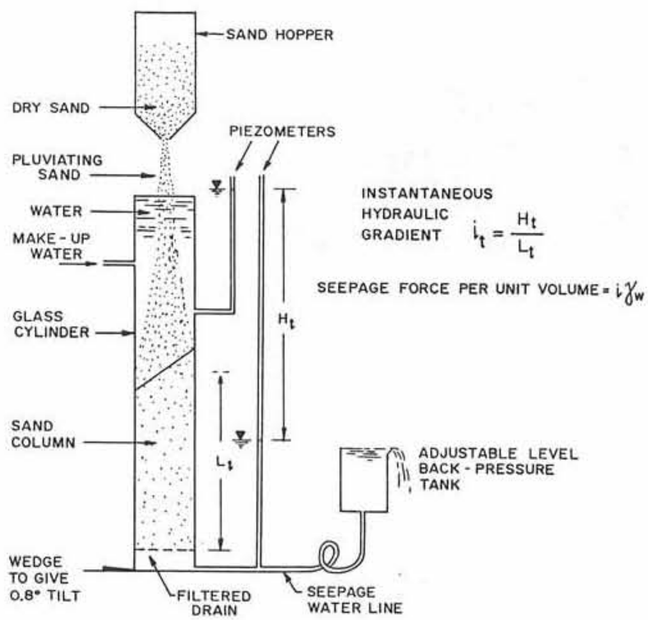


FIG.6.- DENSITY AND TILT TEST APPARATUS USED AT CORK

The test set-up was as follows: A glass cylinder measuring 850 mm long and 90 mm diameter was fitted with a filtered drain at its base. This cylinder was kept full of water. Each test consisted of discharging 1500 g of dry sand from an overhead hopper into the cylinder, under the influence of a constant seepage gradient. The seepage was developed by connecting the base drain to a back-pressure tank. By raising or lowering the back-pressure tank the hydraulic head differences acting across the sand column could be varied. The head difference was measured using two piezometers. The headwater peizometer measured the fluid density increase due to the sand in suspension; the tailwater piezometer accounted for hydraulic losses in the system. At any time (t) the hydraulic gradient (i) acting on the sand column is equal to the ratio of the difference in piezometer elevations (H_t) and the mean length of the sand column (L_t).

Each test was conducted by opening the orifice of the sand hopper and then continually adjusting the elevation of the back-pressure tank in order to maintain the appropriate differential head across the growing sand column. In this way, a sand deposit was formed which was at all times subjected to a predetermined constant hydraulic gradient, $i=H_t/L_t$. The resulting sand density was established by measuring the volume of sand in the cylinder at the end of the test (while the gradient was still imposed) and then weighing the entire sand mass after oven drying. Using this apparatus a total of 43 tests were carried out which produced data for three pluviation rates and several different seepage gradients. The sand discharge rates were 5.4 g/s, 2.8 g/s and 0.83 g/s and are referred to as fast, intermediate and slow, repectively. The hydraulic gradients ranged from 0.5 upwards to 10 downwards.

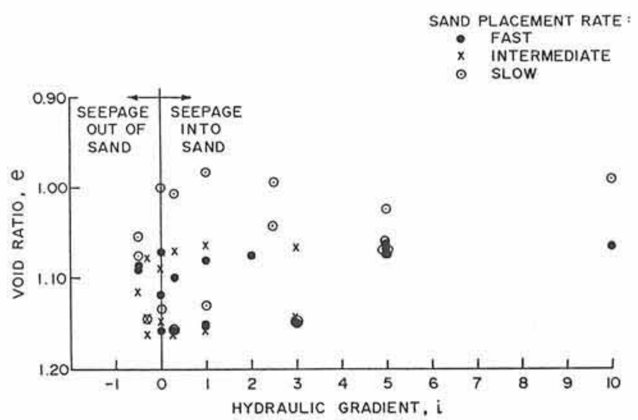


FIG.7.- RELATIONSHIP BETWEEN SAND DENSITY AND HYDRAULIC GRADIENT BASED ON CORK CYLINDER TEST DATA

The results of these tests are shown on Figure 7, where the dry density (in terms of void ratio) is plotted against hydraulic gradient. From this it may be seen that there is apparently no correlation between seepage gradient and sand density. This finding contradicts the initial concept. However, as will be discussed later, there is a redeeming feature in this data which led to a modified concept, and possibly to a more fundamental understanding of the behaviour of sand deposition.

Tilt Tests

The density test apparatus described above was intended to serve a double purpose. It had earlier been found that by tilting the glass cylinder slightly, the top of the depositing sand would form as an inclined surface. When sand discharges symmetrically into a cylinder, the sand surface formed during the course of placement is roughly horizontal. A slight tilting of the tube is sufficient to upset this balanced depositon. Any imbalance causes sand to build up on one side of the tube more than the other, thus producing a slope at the surface of the sand. This phenomenon is quite reproducible and yields a relatively planar surface.

In 26 of the density tests discussed above the cylinder was tilted 0.8° and the inclination of the resulting slope was measured while the gradient was still in effect. The slope steepness was found to vary, both with the rate of pluviation and with the seepage gradient being exerted across the sand column. These results are shown in Figure 8. For each of the pluviation rates it is possible to draw a curve through the data which suggests that, for the specific case of the very confined environment of the test cylinder, slope steepness is related to the rate of sand deposition. The results also indicate that up to a point, steeper side slopes are a function of hydraulic gradient. It should be noted here that slopes steeper than the angle of repose of the sand only remained stable while the inward seepage gradient was maintained. When the seepage was stopped the slopes ravelled back to the angle of repose.

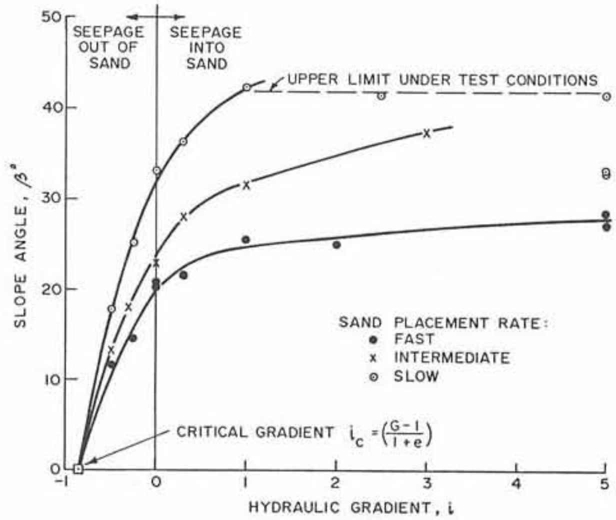


FIG.8.- RELATIONSHIP BETWEEN SLOPE ANGLE AND HYDRAULIC GRADIENT BASED ON CORK TILT TEST DATA

In these tests it was possible to introduce controlled upward seepage through the sand. This outward flow of water led to flatter slopes, to the extent that, as the gradient approached the critical (or quicking) gradient, the slope inclination approached the horizontal. The initial implication drawn from this data was that the flat side slopes normally associated with underwater sand fills is a result of excess pore pressures causing outward seepage forces. The flatter slopes observed for faster sand placement rates were attributed to higher pore pressures arising within the sand mass because of the greater energy associated with the more rapid deposition. This topic will be discussed further following presentation of the Ottawa test results.

Although the tilt test data relating slope steepness to hydraulic gradient is interesting in its own right, the more enlightening aspect of the data is related to sand density. During the course of the work it was noticed that there was a significant density difference between sands that were built on a steeply inclined surface and those that were deposited on a flatter surface. Consequently, the density data was plotted against the side slope angle measured at the surface of the sand at the end of each test. This plot is shown on Figure 9, where it may be seen that, in comparison with the random density relationship depicted on Figure 7, there is a discernible correlation between sand fill density and the slope of the sand surface. Examination of the stratification within the test columns indicated that the slope steepness remained virtually constant as the column of sand continued to build, therefore, the final surface slope was a good representation of the slope which prevailed throughout the test. Since the magnitude of the shear stress acting on surficial grains is a direct function of the surface slope inclination this data suggests the idea that the density of sand deposited underwater is to some degree dictated by the shear stress field into which the particles fall.

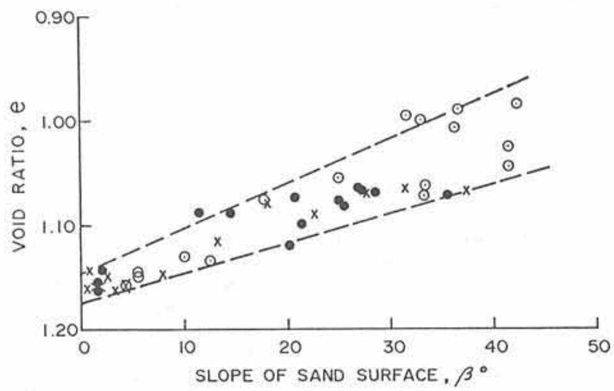


FIG.9.- RELATIONSHIP BETWEEN SAND DENSITY AND SLOPE ANGLE BASED ON CORK TILT TEST DATA

Tentative Conclusions

The simple small scale tests described above led to the following tentative conclusions:

The inclination of the side slopes forming a sand fill placed through water is influenced by the magnitude and direction of seepage forces acting on the sand mound at the time of sand deposition.

The density of sand packing is not influenced by seepage forces but appears to be related to the slope of the fill surface.

These statements are consistent with geotechnical theory. Since the sand/water interface is an equipotential surface, seepage forces act in a direction normal to the slope. Because seepage forces contribute to normal effective stresses they would be expected to influence slope stability. Sand fill density on the other hand, is not significantly improved by normal forces. Common practice is to compact granular soils by means of vibratory loading, which is essentially a matter of subjecting the sand structure to cyclic shear forces.

CONFIRMATORY MODEL TESTING (OTTAWA)

The model work outlined below was carried out during the summer of 1985 in the Hydraulics laboratories of NRC in Ottawa. Apart from NRC's funding requirement for "arms-length" verification testing of the initial Phoenix research, there were several other reasons for undertaking this work. It was necessary to establish that the steeper underwater slopes obtained in Cork could be reproduced using a different sand and a larger model size. In other words, it was necessary to free the initial conclusions from doubts associated with those small scale models and any peculiarities of the sand type used. The earlier model work used a central drain to cause inward seepage; this method could not be used in the field. It was necessary, therefore, to find out if similar beneficial results could be obtained using a ring of vertical wells such as might be used in a field application. Also, the fact that there appeared to be no correlation between density and seepage forces (normal stresses) warranted further investigation using a larger cylinder and a slurried sand fill. Finally, some testing was needed to see if sand erodibility could be modified using seepage forces. With these objectives in mind, Phoenix drew up a testing program which was subsequently approved by NRC. Phoenix designed and fabricated the testing equipment and apparatus necessary to pursue this program and then turned the testing over to Golder Associates' engineers who carried out the work.

The Ottawa program was divided into three separate series of tests to assess the effect of inward seepage forces on sand fills:

A. Construction of models to measure side slope angles and penetration resistance.
B. Direct measurement of sand density.
C. Wave flume tests to measure sand erodibility.

The sand fills tested at NRC were formed using a sand slurry placed through still water. Each sand fill was subjected to a constant value of hydraulic head differential during placement. The "islands" were totally submerged and did not break the water surface even during wave flume testing. Two types of sand were selected for testing and the gradations of those sands are shown on Figure 2. The silt in the Type III sand made visual observation very difficult and consequently the main body of work was done using Type II which is a clean subangular quartz sand.

Series A - Model Islands

The apparatus and testing arrangement is shown schematically on Figure 10. An existing 3.0 m wide and 2.7 m deep flume was divided into two compartments separated by a 0.8 m high wall. The smaller compartment was used for sand storage; the larger one was used to build the model islands. Both compartments were filled with water. Sand fill was pumped as a dense slurry (about 30% sand by volume) into the larger compartment using an air-activated, double-diaphragm pump and the suction/discharge arrangement shown on Figure 10. The pumping rate was about 2 l/s of fluid. The seepage apparatus consisted of a circular header to which vertical wells were attached. Three different header sizes were used with nominal ring diameters of 0.5 m, 0.7 m and 0.9 m. The wells consisted of 400 mm long, 13 mm tubing with the lower 150 mm perforated and covered by a 140 micron steel mesh. Two suction lines were attached to the 60 mm header pipe and connected to a back-pressure tank through a valve assembly. With this arrangement, water was drawn into the wells by the siphon effect created when the back-pressure tank was lowered beneath the water level of the main tank.

The model construction was carried out in the following manner: A 150 mm thick base course of sand was placed in the main tank and the surface was leveled. The seepage header and wells were lowered onto the sand surface and pushed into the sand bed to bury the perforated length of the wells. The tank was filled with water to a level of 230 mm below the top. The nozzle of the discharge pipe was fixed at 50 mm below water level in a position directly above the central axis of the header. Seepage flow was commenced by lowering the back-pressure tank to produce the desired differential head. Sand slurry was then pumped from the stockpile tank into the water above the seepage ring. As the submerged sand mound formed, the sand level at the line of wells increased leading to deeper burial of the perforations. As soon as the perforations were buried by about 100 mm, the header was raised by means of a hoist, until the sand cover above the top of the well screen was reduced to about 50 mm. During the period while the ring was being lifted, the slurry discharge was interrupted. This sequence of discharging slurry and then incrementally raising the seepage ring was continued until the surface of the sand mound was within about 0.3 m of the discharge nozzle. At this point, the sand filling was terminated but the seepage flow was maintained. Finished models were 1.6 m to 2.4 m in diameter and from 0.4 m to 6 m high. A total of 20 models were constructed in this way, seventeen using the clean 170 micron sand (Type II) and three models using the 105 micron silty sand (Type III). Of the 17 tests conducted with the clean sand, 11 (standardized) tests were performed using the medium size header ring, with all wells in place and constant suction. In the remaining six tests, procedural variations were introduced such as changing the header size, removing some wells or interrupting seepage flow.

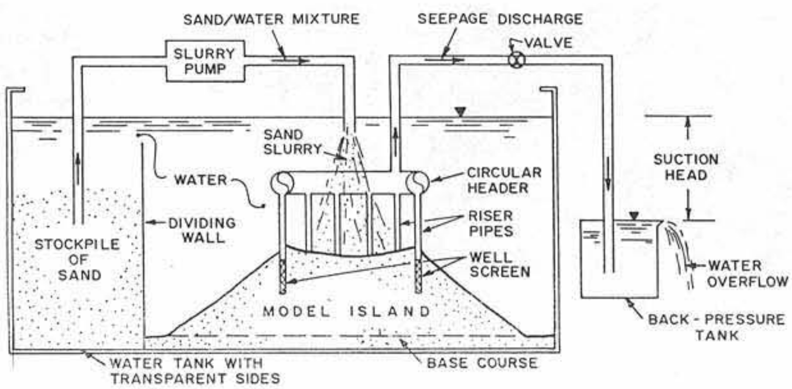


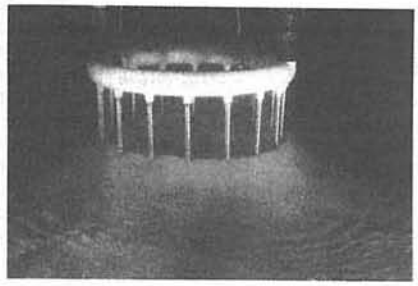
FIG.10.- MODEL ISLAND CONSTRUCTION APPARATUS USED AT OTTAWA

The photographs on Figure 11 show the Phoenix seepage ring and three stages of model building. In the early stage, sand can be seen accumulating in an annular ring coincident with the line of wells. The ripples on the sand bottom outside the fill indicate that there is significant energy being carried by the slurry jet. Both the inside and outside slopes of the annulus of sand are steep. The intermediate stage shows the sand slurry falling on a mound which is growing symmetrically beneath the discharge nozzle. At the end of construction the steep side slopes typical of this process are obvious.

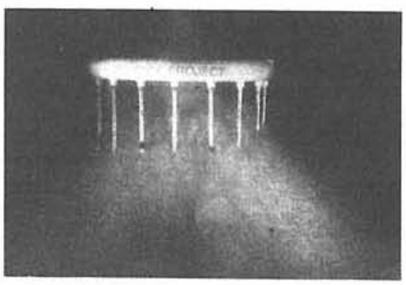
Slope Angle

With the suction still maintained, physical measurements of the sand mounds were taken along two orthogonal sections. The results for a typical model are shown on Figure 12. In this case it may be seen that the sections of the slope close to the wells are steeper than 40°. Such unnaturally steep slopes could only stand while suction was being applied to the fill; once the seepage was cut off the outside slopes gradually ravelled back to about 29°. The silty sand responded in substantially the same way as the coarser, cleaner sand with sections of the slopes being steeper than 40°.

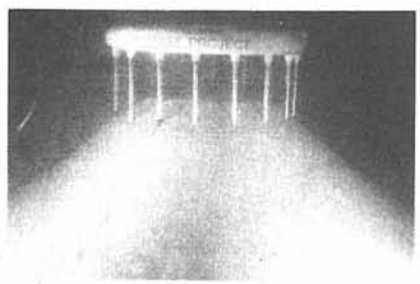
(a) Drainage Header and Wells



(b) Early Stage of Construction



(c) Slurry Discharge



(d) Completed Underwater Model

FIG.11.- PHOTOGRAPHS OF MODEL ISLAND APPARATUS AND CONSTRUCTION PROCESS TAKEN DURING OTTAWA TESTING

The results of the 11 standardized tests are summarized on Figure 13, where average side slope steepness is plotted against the differential head applied across the seepage system. The observations made during this series of tests may be summarized as follows:

a) Side slope steepness during construction can be increased by applying a suction to the sand fill. This method works for both of the sand sizes tested.

b) Flat slopes such as observed in nature could not be produced in the laboratory at this scale.

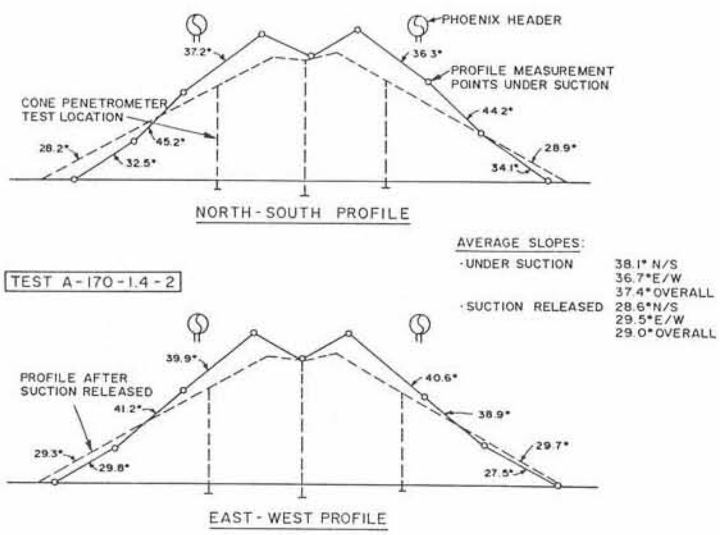


FIG.12- TYPICAL MODEL ISLAND GEOMETRY FROM OTTAWA TESTING

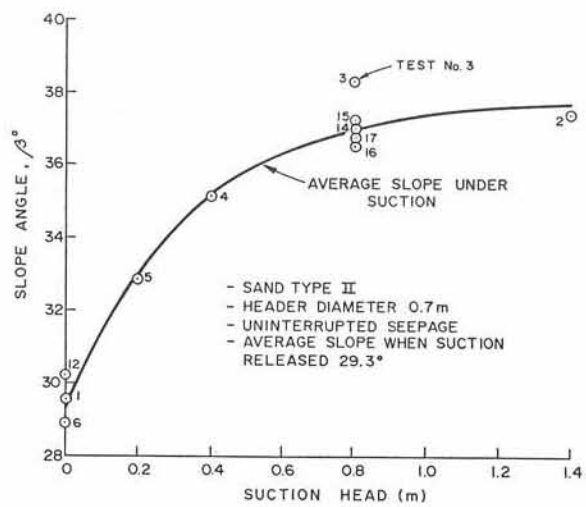


FIG.13.- RELATIONSHIP BETWEEN SLOPE ANGLE AND SUCTION HEAD BASED ON OTTAWA MODEL ISLAND DATA

c) The steepest slopes were closer to the top of the mound and nearer to the influence of the wells.
d) Beyond a head differential of about 0.8 m there was no appreciable improvement in slope steepness for this size model.

An incidential observation was made while hoisting the seepage ring. The force required to lift the header was very much greater when the suction was still active than when water flow was cut off. This additional force is due to the anchoring effect produced by the increased effective lateral stress acting around the wells.

Penetration Resistance

An attempt was made to evaluate the packing density of the sand fill in each of the models. The best method to determine the average density would have been to measure the sand volume accurately and then remove the entire volume of sand, then weigh it after drying. This was not done because of time and cost constraints. As an alternative it was decided to do miniature cone penetration tests. A right cylindrical probe with a 60° apex cone and 280 mm² cross sectional area was constructed for this purpose. Prior to doing the penetration tests the seepage flow was stopped and the side slopes allowed to stabilize. The probe was then pushed into the sand fill at five locations, as shown on Figure 12; one in the centre and four on the side slopes near the island rim.

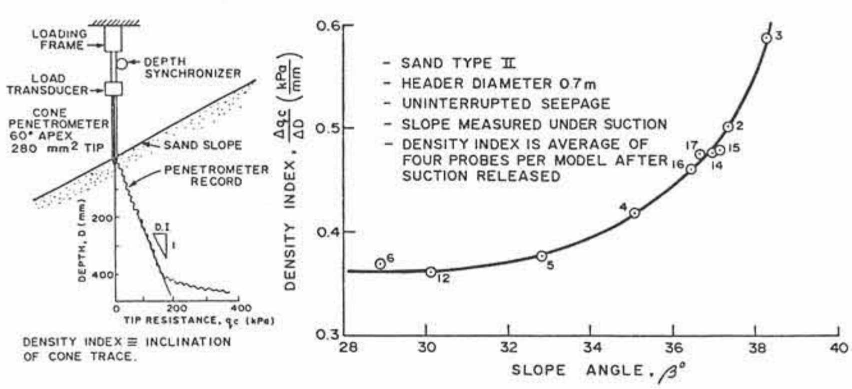


FIG.14.- RELATIONSHIP BETWEEN DENSITY INDEX AND SLOPE ANGLE BASED ON OTTAWA MODEL ISLAND DATA

The resistance to penetration was recorded using an electronic load cell. This method gave a qualitative indication of relative fill density for different models, but it could not be directly related to absolute values of density because of the lack of confinement close to the slopes. The sounding profiles showed a linear increase of resistance with depth and it was decided to use the slope of this profile i.e., the rate at which penetration resistance increased, as the measure of packing density.

The results of the probe measurements are summarized on Figure 14 for 10 of the 11 standardized test mounds shown on Figure 13. The probe malfunctioned during Test No. 1 and this data was therefore deleted. The penetration resistance for the average of the four individual soundings per model is plotted against the average side slope angle for that test. It should be noted that slope angles were measured while the seepage flow was occurring but the penetration tests were made after the seepage was cut off. The data points show a strong correlation between penetration resistance and slope angle. This suggests that sand density is a function of the construction slope angle as was previously suspected at Cork. A more surprising result is that the penetration tests carried out in the centre of the islands showed a decrease in resistance with increasing seepage force. This is directly contrary to what was expected and this aspect will be discussed later.

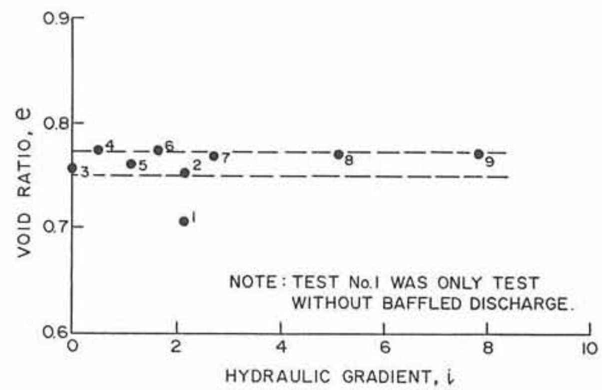


FIG.15.- RELATIONSHIP BETWEEN SAND DENSITY AND HYDRAULIC GRADIENT BASED ON OTTAWA DENSITY TEST DATA

Series B - Density Tests

The testing carried out at Cork had indicated that the density of sand fill was not improved by being placed under the influence of inward seepage flow. The following tests were performed in Ottawa at larger scale to see if the earlier results were valid and not just an artifact of the equipment and scale size. A 250 mm diameter, 370 mm high cylinder with a filtered drain in the base was used. This cylinder was submerged in the model tank and sand slurry was discharged into it in the same manner as was used to construct the model sand mounds. A baffle was used between the discharge nozzle and the top of the cylinder in all but one test. The sand was observed to form by depositing on a flat surface. For each of the ten tests performed, a fixed differential head was used throughout the filling process. After filling, the seepage flow was cut off and the cylinder was recovered from the tank. The surface was struck off and the known volume of sand was oven-dried and weighed. The results are summarized on Figure 15. It is evident from this data that placement of sand under an inward seepage force has, in itself, no effect upon sand fill density.

Series C - Wave Flume Experiments

This testing was undertaken to determine to what extent inward seepage would improve the resistance of sand fill to erosion. The test arrangement was designed to measure sediment transport during the passage of a wave train across a submerged sand mound, rather than the effects of wave run-up on a beach.

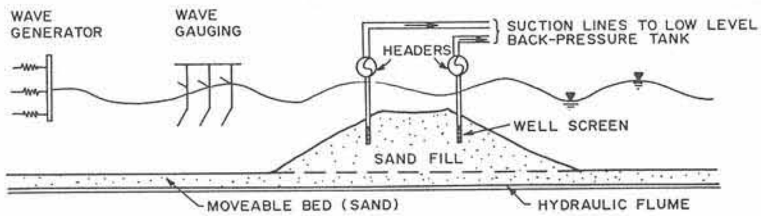


FIG.16.- WAVE FLUME APPARATUS USED AT OTTAWA

The general test arrangement is shown schematically on Figure 16. The central piece of equipment was the 1.3 m wide Ottawa Wave Flume, where it was possible to generate and monitor a wide spectrum of wave forms. Sand fills were built inside the flume under still water conditions using the same method as was used for the Series A testing. The fill sections in this case were of constant section across the width of the flume, rather than circular, as in Series A, i.e., an embankment shape rather than an island. In order to form this shape, the discharge nozzle was moved back and forth across the flume between two parallel lines of wells. The fill was brought to within 150 mm of the water surface. Following construction of the sand fills the suction (in cases where suction was used) was shut off to allow the fill to recline to its angle of respose ; this ensured a constant embankment shape irrespective of the suction imposed during construction. Transducers were then embedded in the fill at various depths to monitor pore pressures as a function of wave action. The wave climate suggested by NRC Hydraulics engineers and adopted by Phoenix, was a 110 mm high wave of 1.46 second period with a two hour storm duration. The experiments were recorded by a video camera which viewed the sand fill and wave passage through a window in the flume wall. A total of 12 tests were performed in this manner and the results are summarized in Table 1. Because some of the fills liquefied under wave loading the results will be discussed under two separate headings.

Liquefaction

The first two tests (No. 1 and No. 2) were built with the well system in place but without applying suction, either during construction or during wave loading. These tests were intended to provide base data against which to measure the amount of improvement that seepage forces would provide to the surficial sand fill. As it turned out these "untreated" fills liquefied in a most dramatic fashion within seconds of being subjected to the design wave. The video records of these events, where the upper third of the embankments turned to a fluid and collapsed is a remarkable illustration of sand liquefaction. Following the initial loss of mass the remaining fill actually could be seen to densify under the influence of the cyclic stresses imposed by the passing waves.

These video records together with the continuously monitored peizometric pressures provide a mass of data which may form the basis of a subsequent paper. Figure 17 is an example of these records.

TABLE 1. - NRC WAVE FLUME TESTING SUMMARY

Test No.	Header Spacing (m)	Suction Applied (m) Construction	Erosion	Comments
1	0.80	0	0	Liquefied
2	0.80	0	0	Liquefied
3	0.80	1.0	1.0	Stable
4	0.80	0	0	Stable under 20,40,60, 80,100 mm sequence. Later liquified under 100 mm waves.
5	0.80	0.5	0.5	Stable
6	0.80	0	0	Stable under increasing wave heights.
7	0.35	1.0	1.0	Stable
8	0.35	1.0	1.0	Stable
9	0.35	1.0	0.1	Stable
10	0.35	1.0	0.5	Stable
11	0.80	1.0	0.5,0.4,0.3, 0.2,0.1,0.05, and 0.	Stable while suction incrementally reduced to zero.
12	0.35	1.0	0.5 and 0	Stable while suction reduced to zero.

Test No. 4 also was built and tested without the benefit of applying suction to the fill. In this case, however, the wave height was gradually increased from 20 mm to the full test height (100 mm) in increments of 20 mm in an attempt to determine the wave height which would initiate liquefaction. The fill did not liquefy under this sequence. After allowing the water to become calm, the fill was then subjected to the full design wave, but this time the wave was generated in a single increment and liquefaction did occur. Test No. 6 was conducted in the same manner as Test No. 4 with the wave height being gradually increased from 20 mm to 100 mm. Liquefaction did not occur and the test was carried to completion to measure erosion. Liquefaction did not occur in any of the tests where the fill was built under a suction head, even when the suction under wave loading was marginal, as in Test No. 9 (0.1 m), or gradually reduced to zero as in Tests No. 11 and No. 12. These results suggest that the Phoenix process produces a sand structure that is sufficiently dense to withstand failure under cyclic loading of a reasonably large magnitude.

Erosion

The amount of erosion that took place during the course of each test was measured by taking profiles of the sand in the vicinity of the mound, both before and after the passage of the wave train. The main test variables were the suction heads applied during construction and during wave loading, the spacing of the suction header manifolds, and the depth of burial of the well screens. The best set of comparative data is from Test No's. 7, 8, 9, 10, and 12 where the suction head used to build the mounds was 1 m and the header spacing was 0.35 m. This data is shown on Figure 18, where the erosion is quantified in terms of the volume of sand lost from the mound and in terms of the depth of sand scoured. These parameters are plotted against the suction head that was exerted during exposure to the test wave climate. It is apparent from both these measures that inward seepage has a significant effect on the reduction of erosion.

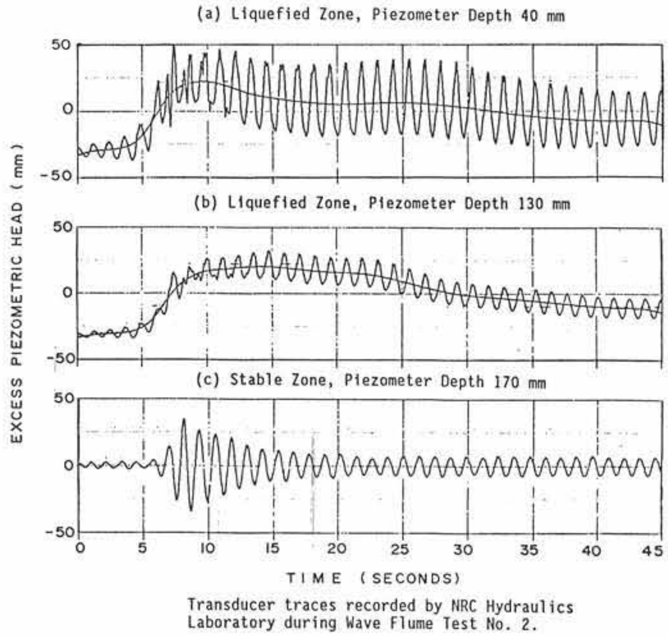


FIG.17.- SELECTED PORE PRESSURE RECORDS FROM OTTAWA WAVE FLUME TESTS

DISCUSSION AND INTERPRETATION OF TEST RESULTS

Slope Steepness

The fact that side slopes can be built more steeply underwater with the aid of inward seepage seems to have been established in the model studies. What has also been demonstrated by the models (excluding the Tilt Tests) is that very flat slopes, such as those recorded in the field, cannot be reproduced in the laboratory. This requires some explanation. During the early stages of this work, the author adopted a pseudo-static approach by considering that the side slopes achieved during fill placement underwater were simply a matter of slope stability, where the limiting slope was a direct function of the level of pore pressure within the sand mass. By this reasoning, very large pore pressures would lead to very flat slopes; the extreme case of horizontal slopes being consistent with pore pressures equivalent to the critical hydraulic gradient. In qualitative terms, it seemed reasonable to assume that high pore pressures would exist within a sand mass due to the dynamics of sand placement. It can be shown by such mechanisms as the Impulse-Momentum Theory that the energy introduced into the vicinity of a sand mound by the dredge discharge and the falling slurry is converted into water pressure within the mass. The higher pore water pressures beneath the slurry discharge would result in seepage flow away from the centre of the fill towards the outside slope, thus reducing stability and slope inclinations. In quantitative terms, the mathematical model summarized in the Appendix was useful in understanding the laboratory test results. This model should also be useful in accounting for the very flat slope angles observed in numerous civil-marine sand fill structures. But, in practical terms, it is not possible to justify the high pore pressure levels which would be necessary to cause slopes of the order of 5° in large fills. The energy required does not seem to be available in most instances - a point which was borne out by the small laboratory models themselves. As discussed below, the answer to this physical phenomenon is now believed to be related more to sand packing density than to slope stability.

Sand Density

The density testing to date consistently supports the conclusion that subjecting a sand to inward seepage forces does not in itself produce a denser packing. Seepage forces act in the direction of the water movement, i.e., parallel to the flow lines. The surface of the fill is an equipotential line and consequently the flow lines are normal to the sand/water interface as is shown on Figure 1. Therefore, the effect of seepage forces on a submerged sand is to increase the normal stresses on the sand without changing the shear stresses. Viewed thus, it is not altogether surprising that seepage forces do not improve packing density, since we know from experience that, although normal stresses are effective in consolidating cohesive deposits, it is necessary to introduce shear stress energy into a non-cohesive mass to decrease void ratio by physically moving grains into a closer packing arrangement.

If the general statement above is correct, why were improved densities recorded in some tests reported here? The answer appears to be surprisingly simple. When a sand grain settles on the side of the fill during construction, it comes to rest on a slope. Because it is on a slope, it is in a shear stress regime. The mere fact that the sand grain is on a sloping face means that it is subjected to a shear stress. The steeper the slope the greater the shear stress. The slope steepness is controlled by seepage force; the shear stress is proportional to slope steepness; and the density is a function of shear stress. Therefore, it is only indirectly that seepage forces improve density and this density increase is only to be expected in the vicinity of the slope.

It is important to note that the permanent improvement in densities obtainable close to a sloping surface is only achievable during the period of construction. In an existing fill, individual sand particles at depth are burdened down by the weight of the soil overlying them. In order to move into a closer packing, a considerable amount of energy is required to overcome the frictional and kinematic resistance to physical relocation. In fact, if this were attempted in a loose submerged sand, the energy input required to densify a deposit at depth could result in a liquefaction failure of the sand mass. This undesirable aspect of densifying an existing submerged sand is not present in the situation discussed here because closer packing is achieved on a continuing basis during sand placement. As each grain falls onto the surface of the fill it rolls into a packing that depends on the slope steepness. It is then held in place by its own frictional resistance to sliding. The ability of the grains to move into closer packing is not inhibited by any oveburden load. Also, there is no deleterious generation of entrapped pore pressures, since the particle is still at the fill surface, i.e., the drainage path is zero length. From this line of reasoning, it appears that the most efficient and effective time to improve the density of a sand fill is while it is being placed. To some extent this may be accomplished simply by depositing it on a sloping surface.

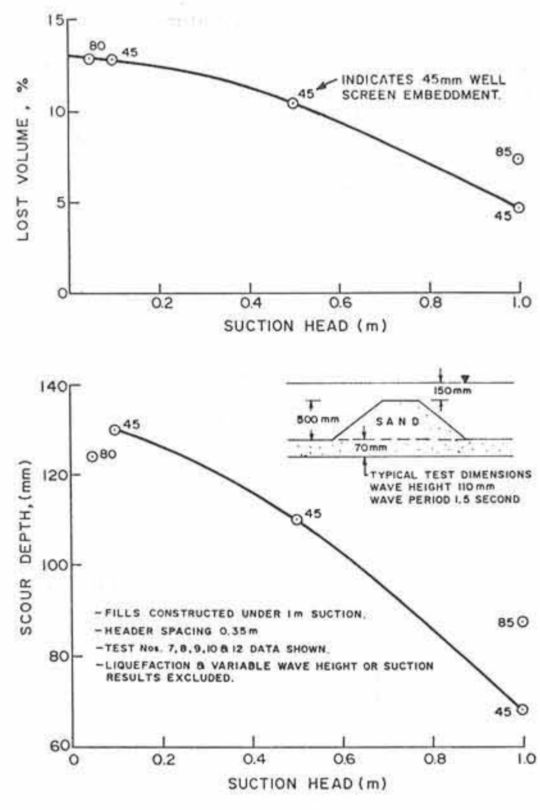


FIG.18.- RELATIONSHIP BETWEEN EROSION AND SUCTION HEAD BASED ON OTTAWA WAVE FLUME DATA

The cone penetration work carried out on the Ottawa models showed that when suction is used, the inside part of the fill was looser than the perimeter. The greater the suction and, consequently, the denser the outer ring, the looser was the interior. This apparent anomaly is consistent with the author's experience of some sand fills, where it seems that the loosest fills are formed when sand is dredged into a confined space within rigid (unyielding) side walls.

It can only be speculated that this may be because sand, when deposited within a confined area, tends to accumulate under a relatively flat surface where it would be unable to attain the closer packing brought about by sedimentation on a slope.

Erosion Resistance

The benefits of suction in increasing resistance to erosion is likely to be readily apparent to geotechnical engineers. The inward flow of water results in an increase in the normal effective stresses acting on the surficial sand grains. This effect can be visualized either as an increase in particle "weight" or as an "apparent cohesion" affect at the sand/water interface. This increases the resistance of surface particles to movements stimulated by the drag forces associated with external water movements.

CONCLUSIONS

Both the Cork and Ottawa results suggest that pumping water from within a submerged sand fill during fill placement has the following beneficial results:

i) It causes an increase in particle packing in the neighbourhood of the slopes. The density improvement achieved by this process is a permanent change in the sand structure.

ii) It increases the steepness of the side slopes of the fill. Side slopes steeper than the sand's angle of repose will stand while the suction is being applied, but will ravel back to about 30° when the seepage flow is stopped.

iii) It reduces erodibility of the sand surface. The enhanced erosion resistance remains in effect only while water is being pumped from within the sand mass.

The most enlightening results at both laboratories were unexpected and were by-products of tests done for other purposes. At Cork, a correlation between sand density and depositional slope angle or shear stress was found. At Ottawa, liquefaction of "untreated" sand fills under wave loading was observed. Although these results need considerably more verification before accepting them completely, they do provide the basis for a more credible and coherent explanation of the physical factors that affect submerged sand fills.

The starting hypothesis was that unsatisfactory sand fill characteristics could be attributed to high pore pressures generated within the fill as a result of the energy introduced into the system by the dumping process. This idea was changed during the course of the work to the following working hypothesis which will form the basis of the next stage of research and development:

a) Sand fills constructed by dumping through water form a loose mass which may initially stand at slopes approaching the angle of repose. Natural forces, such as wave loading or slope steepening by erosion, produce shear stresses within the mass which lead to liquefaction type failures of the fill. The very flat side slopes normally associated with these fills are a result of liquefaction of a loose sand mass.

b) The engineering characteristics of the fill can be improved by pumping water out of the fill during construction. Pumping causes a reduction in pore water pressure that serves two purposes, viz., it eliminates any excess pore pressure within the mass, then upon further depression, it leads to negative pore pressures which induce stabilizing, inwardly acting, seepage forces. The inward seepage forces cause steeper side slopes to build during fill placement. Sand deposited on these steeper side slopes naturally adopts a denser packing because of the shear stresses which exist in the vicinity of such slopes. The density improvement, which is a permanent change in the sand structure, is sufficient to resist liquefaction type failures under subsequent natural loading.

In practice, this method would be used to create a sand fill of adequate density to resist liquefaction of the mass and, incidentally, to produce side slopes of more acceptable steepness. Pumping would be continued until after slope protection material was placed, and possibly, later reactivated as an added measure of safety during severe storms.

Undoubtedly, there is need for further large scale model research work to verify and clarify the concepts presented here. However, the next stage of development planned will be to take the work out of the controlled environment of a laboratory and test it in the field. A relatively large test section will be constructed in a lake or reservoir. At this scale it will be possible to make a quantitative assessment of density using standard insitu techniques. The effect of variations in gradation and silt content will be encountered, although the testing to date suggests that these factors are not of fundamental importance other than in affecting the quantity of water which needs to be pumped. Some development work has already been done on the field equipment required to circulate water through a submerged fill during construction. The field trials will check the functional adequacy and ease of deployment of this system.

ACKNOWLEDGEMENTS

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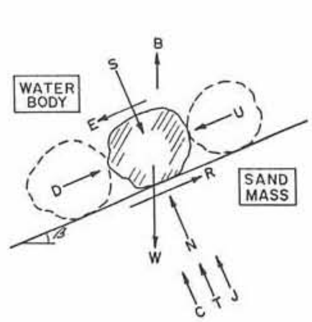
APPENDIX

MATHEMATICAL MODEL OF FORCE EQUILBRIUM FOR SURFACE PARTICLE RESTING ON THE SLOPE OF A SUBMERGED SAND MASS DURING FILL PLACEMENT AND PUMPING OPERATION.



FORCE ON PARTICLE

- B bouyancy
- C excess pore pressure generated by consolidation
- D downslope particle support
- E erosional drag
- J excess pore pressure generated by jet deflection
- N normal intergranular
- R resultant shear
- S seepage from pumping
- T excess pore pressure generated by shear contraction
- U upslope particle push
- W weight

Assuming Limit Equilibrium of Spherical Particle

$$\left\{\cos\beta + (i_s - i_c - i_t)\left(\frac{1+e}{G-1}\right)\right\} \tan\phi = \sin\beta + \left(\frac{v}{v_t}\right)^2 J$$

where i_s is the applied inward seepage gradient

$$i_c = \frac{\Delta h}{\Delta t} \left\{\left(\frac{G-1}{1+e}\right) + i_s\right\}\frac{h}{C_v}$$

$$i_t = \frac{\Delta h}{\Delta t} \left\{\frac{e_{max}-e}{e_{max}+1}\right\}/k$$

β	slope angle
e	void ratio of sand compatible with shear stress regime
G	specific gravity of sand
ϕ	angle of internal frictional resistance of sand
v	erosional velocity against particle
v_t	terminal velocity of particle in water
J	exposure factor to erosional drag
$\frac{\Delta h}{\Delta t}$	rate of sand placement
h	height of sand column subject to seepage gradient
Cv	coefficient of consolidation of sand mass
$e_{max,min}$	void ratios, loosest and densest packing density
k	coefficient of permeability