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EROSION AND PORE PRESSURE GRADIENTS

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ABSTRACT: When a water current along a permeable seabed exceeds a certain velocity, the grains begin rocking and moving along the surface, and erosion has started. The phenomenon is a combined hydraulic and geotechnical problem, when pore pressures are built up in the seabottom and upwards pore water flow toward the seabottom is created. In this paper this problem is simplified as much as possible: A water discharge flume is equipped with a sand bottom. The water flow velocity and the pore water gradient can be changed, the eroded sand mass can be measured, and the whole process recorded on video. The results from 18 tests in 3 test series are shown. The result is not surprising, but hopefully it opens up for new experiments, for instance with burried flexible pipelines, where the combination of erosion and increasing pore pressure causes severe problems.

INTRODUCTION

When a wave train passes a sandy seabed cyclic alternating shear stresses are developed and pore pressure built up, cyclic mobility and even liquefaction may take place in certain soils. If the seabed surface simultaneously is influenced by water currents erosion may also occur, eventually magnified by upwards seepage caused by pore pressure gradients.

When an offshore structure is installed, the wave load is transferred directly from the surface of the sea to the subbottom soil, and the water currents are increased when passing by the structure. The erosion is in this case normally prevented by protection of the seabed.

However, when a flexible pipeline is burried in a rather small depth below seabed, erosion protection is very cumbersome. The effect of surface waves and water currents along a seabed is combined with alternating uplift forces on the tube, when gas and oil pass through, and small deflections of the tube, when oil and gas pressure changes.

In order to study these phenomena a cooperation program was set up between The Soil Mechanics Laboratory at the University of Aalborg and The Department of Marine Civil Engineering at The Technical University of Gdansk in Poland. This paper presents the very first step of this research work. It deals with the simplified problem of simultaneous water current along a seabed and up- or downwards seepage across the seabed.

EROSION POTENTIAL

Whenever there is waterflow into a permeable seabed the hydraulic gradient necessary for the flow motion through the voids results in a seepage force on the bed particles, which is balanced by the gravity of the particles and the contact pressures between the particles. The seepage force can even be physically significant at the sand-water interface of the bed.

Interfacial bed particles are subjected to an upward force whereever water flows out of the bed or a downward force whereever water flows into the bed. If the permeable bed in question is the bottom in a seashore, incipient motion and sediment transport along a coast line may be affected. A careful study of this problem may lead to new solutions for the seashore protection against erosion as well as to more consistent design criteria in the contact area of the structure and the seabed both subjected to wave and current action. Under hydraulic structures the seepage can cause piping and heaving of the bed surface and result in complete failure.

During cyclic loading pore pressures can be built up in the upper layer of the seabed and even complete liquefaction can take place. This phenomenon creates an upwards flow of water, which may cause erosion of the seabed by water current, and results in quite new conditions for structures placed on or in the seabed.

When the water flow along a permeable seabed exceeds a certain value, the critical velocity motion, it will cause erosion and sediment transport. This phenomenon is not only caused by the seapage forces on the interfacial bed particles, as described above, but also caused by the shear stress from the flowing water. If the water flow exceeded the critical velocity in the boundary layer, the sand grains can be moved. When water is flowing into the seabed the stability of a laminar boundary layer is increased as turbulence is depressed. In this case the boundary shear stress is less than it is with an impermeable seabed. When water is flowing from the seabed into the water, it will destabilize the laminar boundary layer and increase turbulence and shear stress.

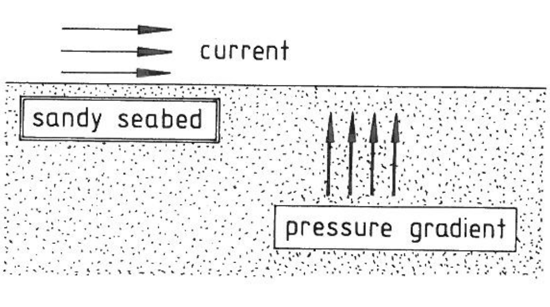


Fig. 1. Sketch for the sandy seabed and waves interaction.

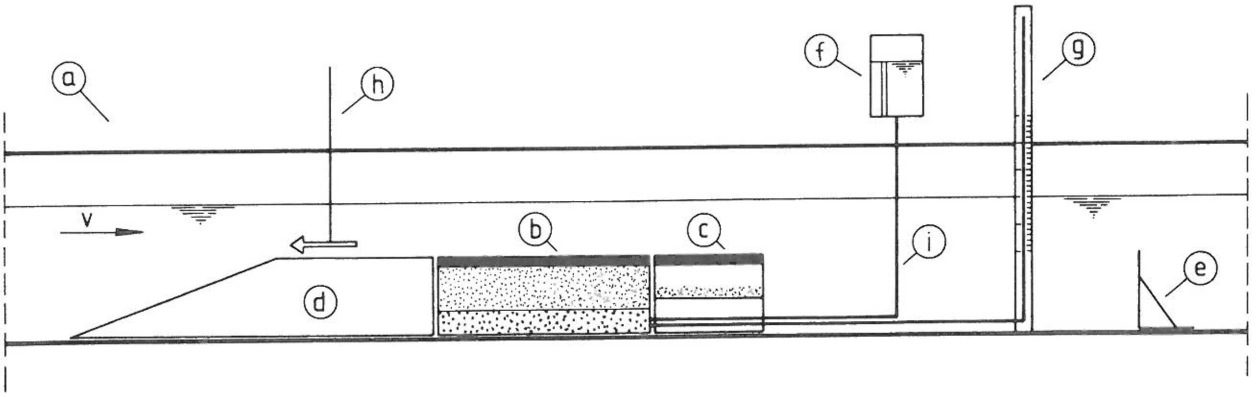
TEST EQUIPMENT

Model tests on the seabed stability have been conducted in a water discharge flume (a). A layout of the research station is shown in Fig. 1. The complete test facility consisted of many individual parts and units.

The flume, 15 m long, together with the circulating storage canal provides with a closed water circuit and is equipped with an electric centrifugal pump where the water inflow can be controlled manually using the gate valve. Box (b) was made of plexiglass and dimensioned 300 x 400 x 150 mm. The box homed the sandy bed sample. Two openings in the lower part of one of the smaller walls were used for the piezometric installation and for inserting of the seepage flow tube. The box (c) was also made of plexiglass. Thanks to a different shape and construction, when comparing with the box (b), the box (c) could play a role of a trap of sand eroded from the box (b) during the test execution. An additional horizontal upper partial horizontal plate prolongs the horizontal bed section beyond the box (b). This solution helps to avoid an eventual water turbulence in a case of flow over the latter sharp edge of box (b). The slope and the horizontal approacing bottom (d) placed before the box (b) created convenient conditions for the water jet flow over the tested element of the sandy bed in the box (b). The main goal of it was to minimize the flow turbulence of the water passing over the box (b) and (c). A rise of the turbulent flow and vortexes on both edges of the box (b) could be extremely dangerous resulting in a destruction of the soil skeleton structure as well as in an untimely generation of the bed erosion. The rubber ribbon gaskets (shown as thick black lines) gave a sufficiently good tightening of the box (b) and (c) along their upper longer edges and lowered the flow turbulence in a vicinity of both longer sides of the box (b). The water gate (e) was put into a position downstream after the box (c) as a protection against creation of a small "waterfall" on the box (c) edge and high flow rate over the sand sample surface just at the beginning of each test. The constant head tank (f) with overflow served as a water supply reservoir for water supply into and water drainage out of the sand bed inside the box (b). The propeller hydrometric current meter (h) and the current meter counter measured the water horizontal discharge flow velocity in the flume. The piezometer was used to indicate the pressure gradient in the sand sample.

TEST SAND

The bed material used was sand "Lund no 00" with the specific density d_s = 2.65. A sieve analysis was performed to obtain some characteristic parameters of the sand. A sand type was estimated as medium where the effective size d_{50} = 0.20 mm, the uniformity coefficient $U = d_{60}/d_{10} = 1.40$ and the coefficient of curvative C_c = 1.03. To have a similar density degree of the sand sample in each test a special additional box with a double sieve was designed and constructed for the sand pouring process. It was one of the demands to preserve the repeatibility of the test results. The medium value of void ratio e = 0.674 was found in several tests before the right series of model tests. One of the most complicated problems in the present laboratory investigation was to obtain a relatively high value of the saturation degree of the sand sample. There are many documents in the world literature: Madsen (1978), Okusa (1985), Verruit (1969), from which it is quite obvious that an unsufficient saturation of a soil model makes test results extremely difficult and complex to be analysed in any way. A creation of a certain vertical pore water pressure gradient was an essential element of the conducted tests. Therefore, a suitable manner of the saturation had to be elaborated. Looking for the most appropriate way of the saturation few solutions were taken into consideration, namely: saturation forced by vacuum, gravitional saturation and saturation caused by capillary forces. Saturation was done, using a boiled water to decrease the air content in the water, in a direction from the bottom of the sand sample upwards to avoid air bubbles in the soil voids. The maximum value of the saturation degree, S = 95%, was achieved from the medium rate gravitional saturation.



a	water discharge flume
b	sand box
c	sand trap
d	slope and horizontale approaching bottom
e	water gate
f	constant head tank
g	piezometer
h	hydrometric current meter
i	seepage flow tube

Fig. 2. Erosion potential test facility.

TEST PROCEDURE

Pouring of the sand into the box (b) was preceded by a filter layer laying onto the box (b) bottom. The main purpose of the filter was to create a uniform distribution of the water pressure below the whole sand layer. Identical pressure conditions in a horizontal cross-section of the sand sample was a fundamental requirement for the tests to be succeeded. As a final stage of the sand sample preparation was the sand pouring using a special method to have a constant value of the void ratio in each sand test and an overfilled sand was levelled by means of a metal ruler and a special unit built on a base of a vacuum cleaner. The sand bed surface levelling operation was carried out with a high accuracy, caution, an[illegible]ce. Only this behaviour gave a chance not to d[illegible] he sand skeleton structure. A delicate levelling made it possible to keep the void ratio value in the sand surface layer on the same level as a value in deeper part of the sample. Afterwards, the gravitational saturation process was performed. A critical moment in water filling of the flume, e.g. when the water level is approaching the sand bed surface, was very sensitive, and responsible operation had to be performed as slow as possible. Missing that moment, at relatively high rate of filling created a big front wave over the sand bed and destroyed the surface carefully prepared.

Incipient motion and erosion potential laboratory tests had a qualitative character and were conducted in three main parts. The horizontal water discharge flow over the plane sand bed was a common feature in all series of the investigation, simulating a sea current. The three series were differentiated by a value of the vertical pore pressure gradient inside the sand bed. The pressure gradient simulated an appearance of pressure in a sea bed under the wave action influence.

The first test series pertained to a case where the vertical pressure gradient equals zero. Each test was divided into two equal parts, each of them with a duration of 30 minutes. The flow rate was indicated during the whole test in 6 min. intervals to evaluate an average value. When the first 30 min. of the test run had been finished, the flow rate was increased up to a value which did not cause any incipient motions of the sand grains. A dry mass weight of the sand eroded from the box (b) into the box (c) was a result. The magnitude of the sand bed erosion after the first test stage was so small that the test could be successfully continued with the same sand bed sample but this time for a bigger flow rate. The second test stage was as long as the first one. Next two values of the horizontal flow rate and the eroded sand weight from the second test stage made one complete test output.

The next two series of the investigation were different from the first one. A vertical pressure gradient was generated in the sand bed (Fig. 1). During the test series no. 2 pressure gradient resulted in the vertical water flow upward through the sand bed. The value of the pressure gradient was close to this one that makes the sand bed liquified. The negative vertical pressure gradient was created in the third test series where the sand bed was affected by water inflow. A magnitude of the negative pressure gradient had the same absolute value as the positive gradient in the series no. 2.

RESULTS AND OBSERVATIONS

Eighteen laboratory tests were performed. Each of three series consisted of six experiments. Using the measured data the resultant Figure has been drawn (Fig. 3). The Figure shows the amount of the eroded sand versus the flow rate of the horizontal water discharge over the porous sandy bed. Three curves (A: no pressure gradient, B: positive pressure gradient, C: negative pressure gradient) are put together in the Figure to make a comparison between the results from all three test series.

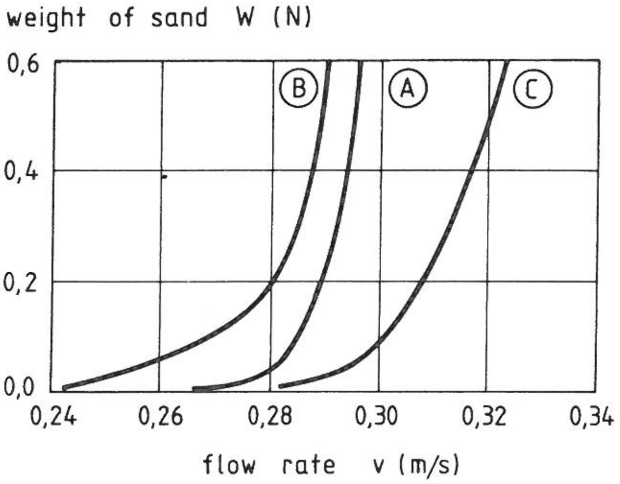


Fig. 3. Amount of eroded sand versus flow rate of horizontal water discharge over porous sandy bed.
A: no pressure gradient; B: positive pressure gradient; C: negative pressure gradient.

A sand bed inspection did not show any changes during the first stage of the test. A small difference was recorded only in series no. 2 where, due to the positive vertical pressure gradient, small ripples were formed and visible. Two or sometimes four tiny ripples were located symmetrically on both sides of the box (b) in its first section.

At the beginning of the second stage of each test the water flow rate was increased, and during a period of 30 minutes, rows of ripples were formed and developed. Three or four rows of ripples were observed. A ripple lay-out was rather symmetrical in series no. 1 (no pressure gradient), but a certain irregularity occurred in series no. 2 (positive pressure gradient). The height of ripples in series no. 1 and 2 was equal to ca. 0.5 cm and 1.0 cm, respectively. The second part of the test in series no. 3 was characterized by only two or three rows of ripples and their height was not bigger than 0.5 cm.

Dimensions of the box (b) limited a value of the horizontal flow rate which could be applied, since an amount of the eroded sand weight cannot be treated as independent from a scale of the sand bed model. For bigger values of the flow rate sand erosion became influenced more by box (b) structure than by natural conditions like a water flow over and through the sandy bed.

The photos show the creation of ripples, when water flows upwards through the seabottom (photo 1), and when water flows downwards (photo 2). Notice that the flow rate in test series no. 2 is smaller than that of the series no. 3. It is clearly shown that creation of ripples is nearly prevented by water inflow into the seabed.

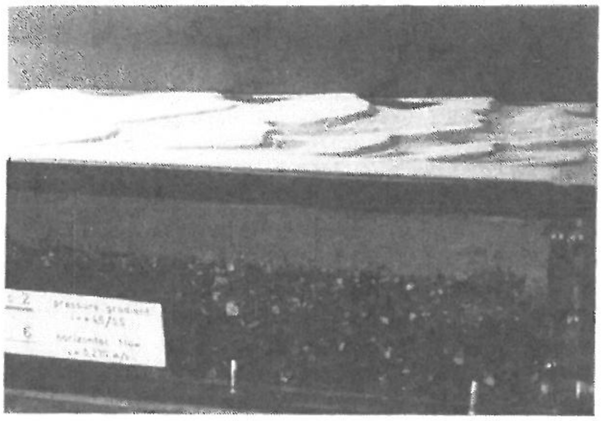


Photo 1. Sand bed surface in test series no. 2 (flow rate v = 0.270 m/sec after 30 min. of test run in stage 2).

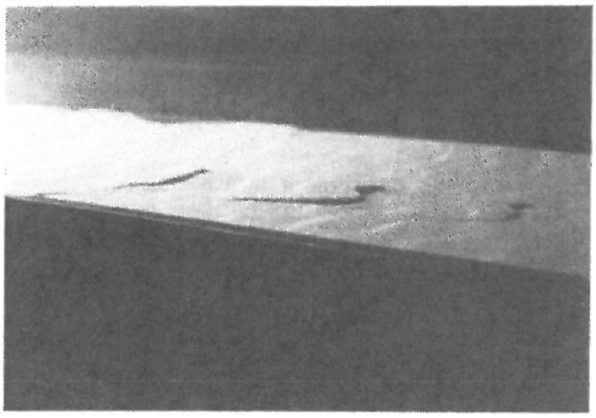


Photo 2. Sand bed surface in test series no. 3 (flow rate v = 0.320 m/sec after 30 min. of flow test run in stage 2).

REVIEW

Eagleson and Dean (1961) note that a permeable bed may influence incipient motion of bed particles under water waves as water flows out of the bed under a wave through and into the bed under a wave crest.

Simons (1955) observed that extensive erosion occured in an otherwise stable irrigation canal during a wind storm which generated waves up to two feet in height. Not withstanding that the wave motion itself induces increased bottom velocities, Simon noted that the stability of the bed may have been destroyed by wave induced flow out of the bed.

Lane (1951) states that for seepage flow into a canal bed containing a wide range of grain sizes, the finer material is transported into the spaces between the larger material and deposited there, thereby forming a more resistant bed because of a concreting action.

Posey (1963) noted that upward flow in a porous bed downstream from a bridge pier increased sediment motion.

Blench (1962) states that he has observed piping failure in flumes resulting from the seepage flow induced by antidune waves.

In a laboratory study, Harrison (1968) concluded on the other hand that on a smooth bed, seepage had hardly any effect on incipient motion and sediment transport if the water was turbid. For flow into the bed using turbid water he also observed a concreting action that resulted in a bed more resistive to motion. Martin (1970) observed that the seepage out of the bed did not affect incipient motion measurably because the seepage force is lost once a sediment particle rocks. Seepage into the bed may either enlarge or hinder incipient motion, depending upon the relative effect of the boundary shear stress and the seepage force, both of which depend on the seepage flow. For a given hydraulic gradient the size of the sand grains is critical regarding incipient motion. For turbid water flow over the bed, fine particles of the mixture may become deposited in the bed, resulting in a concrete-like more resistant bed. Martin gave typical values of the hydraulic gradient for flow out of a canal and in an ocean bed under oscillatory waves.

The effect of fluid injection on the boundary shear stress and on the velocity distribution above smooth and rough walls has been studied by a number of investigators. Turcotte (1960) developed a theory for the laminar sublayer for fluid injection into an incompressible turbulent boundary layer. He stated that for 0.3 mm sand particles the boundary shear stress could be reduced as much as 30% by seepage out of a hydraulic smooth bed. For small values of the permeability and/or of the vertical hydraulic gradient, however, seepage has little or no effect on the boundary shear stress. Eckert et al. (1955) investigated the effect of air injection through porous rough surface on flow in channels.

The effect of suction on boundary layer control has provided much of the impetus for research on flow into a wall. There have also been studies on the effect of suction on flow through pipes. There are only few data available on the effect of suction through porous rough surfaces on the boundary layer flow characteristics. It has been shown by Dutton (1960) that for increasing rates of suction the velocity profiles become more nearly uniform and that the level of turbulence intensity is essentially reduced. The boundary shear stress is increased by suction.

CONCLUSIONS

The erosion potential of a water current along a sandy, permeable seabed subjected to pore water in- or outflow has been studied in the laboratory by performing small scale model tests in a water discharge flume.

The first test series shows the transportation of sand, when no pore water movement takes place. The weight of transported sand per 30 minutes at different flow rates is shown in Fig. 3 as curve A.

The effect of pore water flowing out of the sandy bed with a gradient of 0.73 is shown as curve B. The influence of the hydraulic gradient, even close to the critical one, seems to be rather small. It affects the threshold flow rate to some extent, but for higher flow rates, when the sand weight per 30 minutes exceeds 0.6 N, the two curves are nearly identical.

But seepage into the seabed prevents erosion by increasing the threshold flow rate and decreasing the inclination of the curve C. It is caused by the boundary shear stress as well as the seepage force both of which depends on the horizontal water flow and the seepage. This result can give positive confirmation of the idea of designing a seashore protection against erosion and transport of sand along the shore line by creating an artificial seepage into a porous seabed by means of submerged wells.

Observations of the sand surface during the tests indicate that the development of sand ripples has a major effect on the transportation of sand. The turbulent boundary layer is increased considerably. The movements of sand grains up and down the ripples and the movements of the ripples themselves give the water flow an important additional capability of transport since only very few sand grains are suspended in the water.

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