THE BREACHING OF SAND INVESTIGATED IN LARGE-SCALE MODEL TESTS

Cees van Rhee* and Adam Bezuijen**

Abstract

The physical principles, which govern the breaching process, are analysed. It will be shown that this process involves both geotechnical and hydraulic phenomena. The stability of the surface of the slope and the internal stability are studied. The theories are compared with results from a large-scale experimental programme. Results show that the propagation velocity of the breach is influenced by the permeability and that the resulting slope is gentler as the breach height increases. The breaching process can even become unstable which can lead to failure of a slope over a very large distance.

Introduction

Suction of sand several metres below the original bottom will lead to breaching of sand. The sand will form a steep slope in front of the suction-mouth. The steep slope is not stable and will propagate from the suction-mouth, producing a sand water mixture that flows in the suction-mouth. Breaching of sand is an important process in the dredging industry. The steepness and propagation velocity of the slope determines the sand production that can be achieved. A research programme has been performed to investigate the mechanisms that govern the breaching of sand. This programme included large-scale model tests and theoretical modelling of the mechanism.

Theory

Erosion theories

When a suction pipe is moved forward with constant velocity v_z in a two dimensional situation, the so-called pit production P follows from continuity:

$$P = v_z B \tag{1}$$

The thickness of the sand layer or the physical limitations of the dredge mostly restrict the depth of the pit B, therefore the velocity v_z determined the slope production. However, the forward velocity is limited by the behaviour of the soil body in front of the suction pipe.

* Ham Int. Dredging Contractors, P.O. Box 8574, 3009 AN Rotterdam, The Netherlands during this research: WL | Delft Hydraulics, Product Group Dredging Technology
** Delft Geotechnics, P.O. Box 69, 2600 AB Delft, The Netherlands

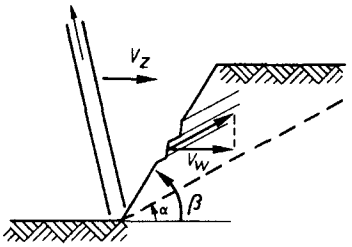

Figure 1: Slope in front of suction mouth.

The slope can be very steep due to the shear dilatancy effect of compacted sand. Dilatancy is the effect that the pore volumes of dense sand tend to increase during shear deformation as result from increased shear stresses. When the sand is saturated with water, this will lead to water under-pressure in the pores. The under-pressure will result in an increased effective pressure and hence increased shear resistance.

In the seventies, the behaviour in front of a dredger was studied at Delft Hydraulics using small-scale two-dimensional experiments. A suction tube was moved forward at the bottom of a flume and the developing slope in front of the suction mouth was studied. From a stability analysis of the surface of the slope the following relation between the forward velocity and slope angle β was derived (Breusers, 1977):

$$\frac{\cot\beta}{\cot\phi} = 1 - \frac{v_z}{v_w} \tag{2}$$

In which v_w was defined as the active wall velocity:

$$v_w = \frac{k_l}{\Delta n} \cdot \Delta \cdot (1 - n_0) \cot\phi \tag{3}$$

In which ϕ, Δn, n0, Δ, and k_l are the internal friction angle, relative porosity increase, initial porosity, relative grain density and permeability respectively. From Eq. (2) follows that at very low velocity the angle of the front slope will be equal to the internal friction angle. The limit speed follows from $v_z=v_w$. In that case the front slope will be vertical. The relative porosity increase is calculated with:

$$\Delta n = \frac{n_l - n_0}{1 - n_l} \tag{4}$$

The active wall velocity (v_w) can be seen as the propagation speed of a vertical disturbance on the slope. By moving a suction mouth downwards a sudden disturbance is created in the soil. The initial steep slope will not be stable in the long term. Fig. 2 gives an impression of the development of a slope after some time. The vertical "wall" will move sideways. The sand from this collapsing front will flow towards the suction mouth. The slope angle below the producing wall is drawn rather steep in Fig. 2. Indeed at relative low production (i.e. small-scale test) this will be the case and a slope angle equal to the natural angle of repose will develop.

In practice however, it was experienced many times that the resulting slope angles were often more gentle. It was suggested that this was due to the erosion caused by a sand-water mixture (acting like a density current) running down the slope

(Koning, 1981), although this hypothesis was not proven. Some years later the influence of the flowing sand-water mixture on the slope development (hydraulic filling) was studied in 1988 by Delft Hydraulics and Delft Geotechnics in the dredging flume of Delft Hydraulics. (Mastbergen and Bezuijen, 1988 and Bezuijen and Mastbergen 1988).

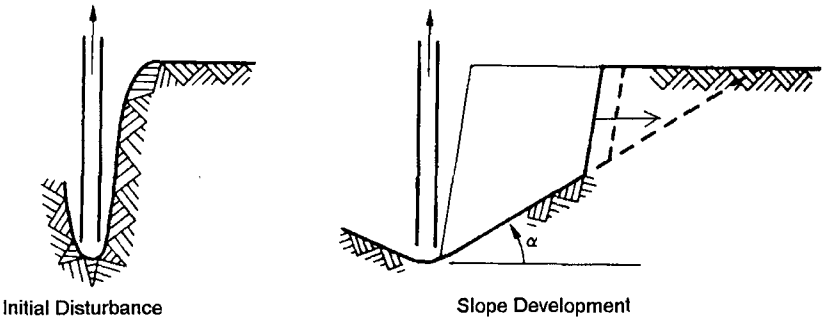

Figure 2: Slope development resulting after sudden disturbance.

It was found that at small production rate, the grain flow on the slope was laminar and slope angles were close to the natural angle of repose. When the sand production increased, the grain flow became turbulent and the slope angle decreased with increased sand flux s [kg/(ms)]. The other important factor was the grain diameter. Coarse sand resulted in steeper angles. The following empirical relation was found:

$$i = \tan(\beta) = 0.0049\, D_{50}^{0.92} s^{-0.39} \qquad (D_{50} \text{ in } [\mu m],\ s \text{ in } [kgm^{-1}s^{-1}]) \qquad (5)$$

The sand production from the slope equals:

$$s = v_w B (1 - n_0) \rho_s \qquad (6)$$

The permeability can be calculated with the following equation:

$$k = \frac{g}{160\nu} d_{15}^2 \frac{n^3}{(1-n)^2} \qquad (7)$$

Combining the equations above, the slope angle of an active wall at a certain depth can be calculated as a function of height. Since the production increases going down the slope, the slope angle will also decrease. Fig. 3 shows the results for two different dense sands. In this figure, it can be seen that at the lower end of a large breaching slope the slope angle will be small. In this example the slope is even gentler for the

coarser sand than for the fine sand because permeability (and therefore v_w en s) dominates over the grain size.

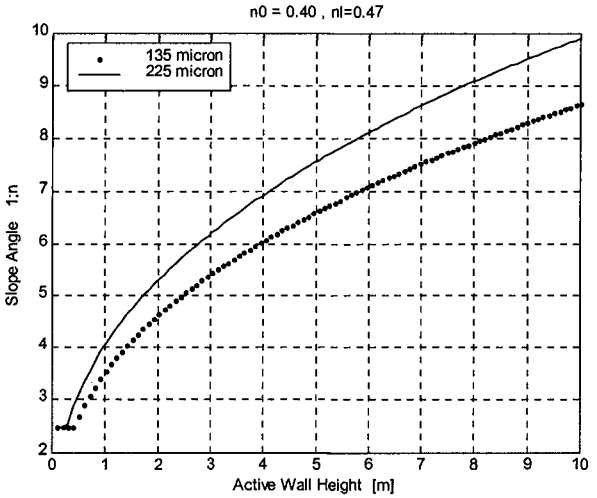

Figure 3: Slope angle at toe of breach as function of breach height.

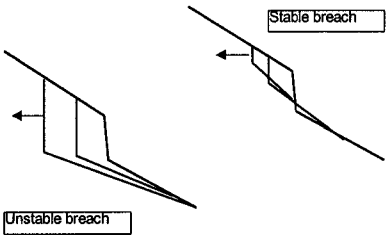

Figure 4: Stable and Unstable breaching.

When an active wall runs up an existing slope as sketched in Fig. 4, the breaching process can become unstable when the slope angle below the active wall is smaller than the existing slope. In that case, the active wall height and thus production will increase. This will lead to an even gentler slope at the toe, which again accelerates the growth of the breach height. This mechanism will go on until the bottom of the active wall reaches the sea bottom. It must be noted that this mechanism can be present in very dense sands. Therefore, it is very likely that this mechanism can be responsible for unexplained "slope liquefaction" in areas where sand was not in a loose state. The mechanism agrees with slope failures observed at the riverbanks of the Mississippi River (Torry, 1995).

Stability of slope

At large propagation velocity of the suction mouth and for a limited breach height, the slope of the breach will be steeper than the slope corresponding to the friction angle of the sand. A slope of saturated fine sand will be stable as long as the angle of the slope α_0 is smaller than the friction angle ϕ of the sand. Above the water line capillary forces can lead to steeper slopes below the water line this is not possible. If therefore the slope is below the waterline and it is steeper then the friction angle, this will always lead to instability. This is not an instantaneous instability. The unstable slope will lead to plastic deformation of the sand and dilatancy (an increase in volume of the sand due to an increase of the pore volume, caused by a different arrangement of the grains, see Fig. 5). Such a dilantancy is only possible if water flows into the sand. Therefore a temporarily stable position is possible for slopes steeper than the friction angle of the sand. In such slopes, there will be dilatancy of the sand leading to a decrease in pore pressure and a water flow into the sand and to a temporarily stable slope. When maximum possible dilatancy is reached, there will be a collapse of the slope.

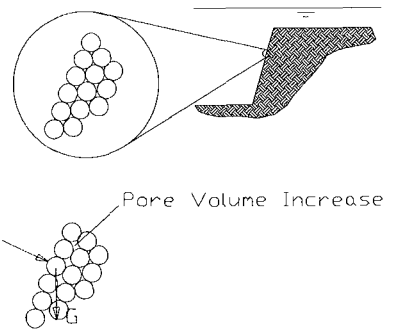

Figure 5: Dilatant behaviour of dense sands.

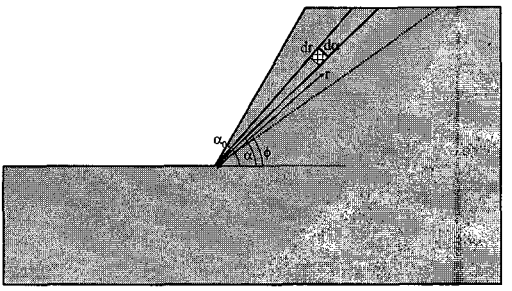

Figure 6: Definition sketch for the calculation of pore pressures in a breach.

If the sand is in this temporarily stable situation, which means that the gradients generated by the dilatancy are just enough to stabilise the soil, the decrease in pore pressure can be calculated. A simplified calculation, neglecting the influence of the groundwater flow, is presented below. Assume that the sand mass within the triangle with a slope angle between ϕ and α_0 (see Fig. 6) is just stable. In that case all particles in that sand mass should be just stable. With the notation presented in Fig. 6, this leads to the following equilibrium equation:

$$\tan\phi = \frac{\gamma' r \sin\alpha.\partial\alpha.\partial r + \partial p/\partial r.r.\partial\alpha.\partial r}{\gamma' r \cos\alpha.\partial\alpha.\partial r + \partial p/\partial\alpha.\partial\alpha.\partial r} \qquad (8)$$

Integration over the angle α and reworking leads to the equation:

$$\frac{\partial p}{\partial r} - \frac{A}{r} p = B \tag{9}$$

with:

$$A = \frac{\tan\phi}{\phi - \alpha_0} \quad \text{and} \quad B = \frac{\gamma}{\phi - \alpha_0}\{\cos\phi - \sin\alpha_0 + \tan\phi.(\sin\phi - \sin\alpha_0)\} \tag{10}$$

Integration over r leads to the minimum pressure (p) that can be expected in the breach:

$$p = \frac{-\gamma.r\{(\cos\phi - \cos\alpha_0)/\tan\phi + \sin\phi - \sin\alpha_0\}}{1 + (\alpha_0 - \phi)/\tan\phi} \tag{11}$$

The pressure drop increases with the slope angle and is linearly proportional with the height of the breach. This equation will be compared with the results of measurements in the section Results.

As long as dilatancy of the sand can provide this minimum pressure, the slope will be temporarily stable. When the maximum porosity of the sand is reached, instability will occur.

Large scale model tests

Two dimensional model tests have been performed in a flume of 32 m length, 1 m width and 2.5 m high at Delft Hydraulics. The flume was filled with fine (135μm) or medium fine (225μm) saturated sand. The density of the sand was controlled by a vibration procedure. In various tests the porosity varied between 38 and 47%. During the experiments a suction mouth was moved through the flume with a constant velocity, varying between 2 and 9 mm/s in the different tests. The suction mouth was moved forward over the bottom of the flume between 0.10 and 0.70 m above the bottom. The resulting breach height varied between 1.50 and 2.2 m

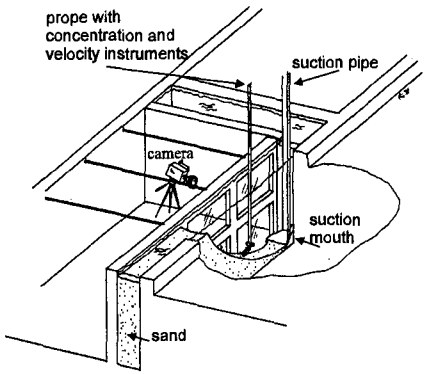

Figure 7: Set-up of the model experiments.

During a test the production, the density and discharge was measured using an EMF and radioactive concentration meter. The pore pressures in the sand and the porosity of the sand were measured by means of a measurement panel that was placed in one of the walls of the flume.

It was expected that during the tests a steep slope angle would develop and that the slope would move constantly forward. This complicated the measurements in the density current on

the slope. It was decided to place the instruments on a carriage that could move over the flume in the same direction as the suction mouth. Close to the instruments, a pressure sensor was placed and the carriage was moved forward automatically until the sensor "felt" the slope. At that moment the carriage stopped and started the measurements. If the process was stationary a concentration and velocity vertical could be obtained because the slope moved away from the instruments. Using this device, the thickness, concentration and velocity of the sand-water mixture could be measured. The process was monitored also by video, through the sidewalls of the flume. The set-up of the experiments is sketched in Fig. 7.

Measurements

Slope angles

Since the tests were two-dimensional, only the slope in front of the suction mouth could be investigated. From the video recordings, the development of the slope angle was followed. It became clear that the description of the active wall velocity according to eq. (3) was not valid at large breach height due to:

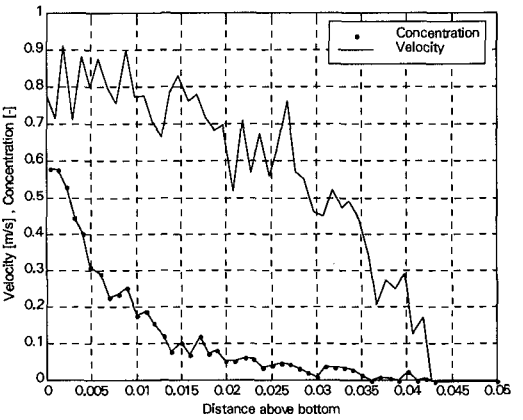

Figure 8: Velocity and concentration profile.

- The presence of a turbulent density current that eroded the sand surface at the toe of the breach leading to a gentler slope which was in accordance with the analysis of section Theory.
- Failure of lumps of sand that was noticed instead of raining of single grains, which occurred at small breach heights.

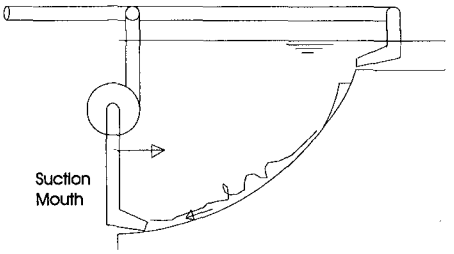

Figure 9: Backfilling at top of the slope.

The effect of the density current on the slope angle

Fig. 8 shows one of the large numbers of concentration and velocity that were measured during the tests. Velocities up to 1 m/s were measured in the density current. It will be clear that this is sufficient to erode the surface of the slope. The influence of the density current on the slope can be investigated by varying

the slope height at a constant forward velocity of the suction mouth. As explained in the theoretical section, the sand-mixture flow must be turbulent to get sufficient erosion. This will only be the case above a certain production level and hence breach height. The sand level in the test flume was limited to 2.3 m.

To simulate the situation for a higher breach, a part of the mixture sucked from the toe of the breach was backfilled at the top of the slope, see Fig 8. The apparent extra height created with this method was approximately 1-1.5 m. During the test, the forward velocity of the suction mouth was 6 mm/s. At a breach height of 2.3 m the slope angle was between 52^0-55^0. During backfilling the apparent slope increased to 3.5 m and the slope angle decreased to below 40^0 as can be seen in the figure below.

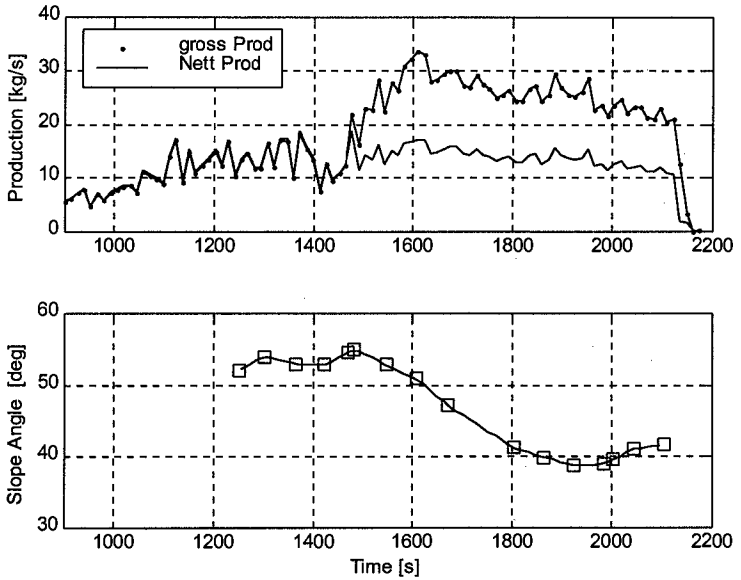

Figure 10: Influence of density current on slope angle

In Fig. 10 it can be seen that at t=1500 s. backfilling at the top of the slope starts. From this moment the gross production increased (part of the mixture is circulating). The net production, which is the amount of soil being removed from the flume, maintains almost the same level. It can be seen clearly however that the large production fluctuations diminish soon after backfilling is started. This is a result from the eroding work of the current at the slope. Before backfilling started, the production was dominated by the sliding of sand lumps from the slope. This is a more irregular process than the erosion process. When the slope angle in Fig. 10 is compared with the theory (Fig. 3) it is clear that the slopes during the tests were steeper. This can be explained by the fact that the slope angles of Fig.3 are derived for a situation were sedimentation dominates, while at the experiments every part of the slope was eroding, due to the forward velocity of the suction mouth. However, both figures show the same tendency.

Porosity and pore pressures

Breaching of sand will lead to a reduction of the pore pressure in the remaining

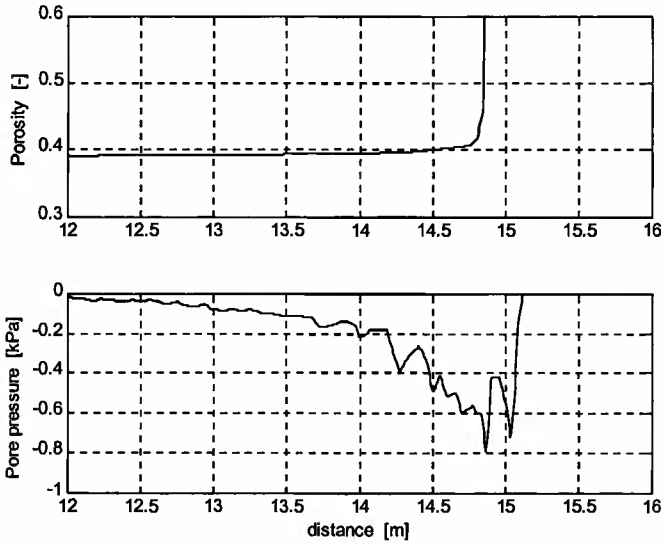

Figure 11: Measured Porosity and porosity changes.

sand, as was explained in the chapter on theory. An example of this reduction is shown in Fig. 11. This figure shows the measured pore pressure and porosity changes on a horizontal plane. The surface of the slope was at that moment situated at x=15.1 m. At this location the reduction in pore pressure disappears.

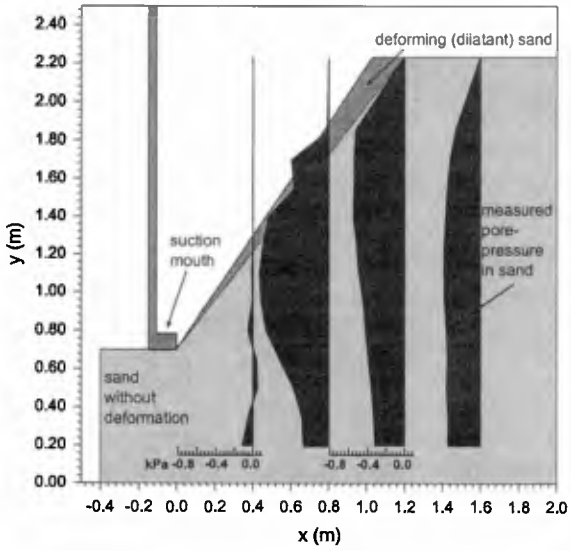

Figure 12: Pore pressure changes in front of suction mouth.

It appears from this figure that the pore pressure reduction is measured more than a metre from the suction mouth. This pore pressure reduction is caused by dilatancy in the sand before it runs

of the slope. However, the electrical density measurements show Fig. 11) that is only limited to a small layer of sand, as is also indicated in Fig. 12. Dilatancy is measured as a decrease of electrical resistance due to the increased porosity. The area indicated functions as a sink. Groundwater flow causes the reduction of pore pressures in the non-dilating part of the sand body. This corresponds with theory.

The measured maximum pore pressure reduction is compared with the results of Eq. (11) in Fig. 13. It appears that using the friction angle of the sand as measured in a triaxial test (35 degrees), Eq. (11) overestimates the pore pressure reduction. However, in densified sand the peak value is always larger than the residual value presented as result of a standard triaxial test. The peak value can be up to 45 degrees. Using this value there is good agreement between measurements and theory for slope angles up to 70 degrees. For larger slope angles the pore pressure reduction is overestimated by theory. This can be caused by density currents that are not taken into account for this model, but lead to an increase of pore pressure.

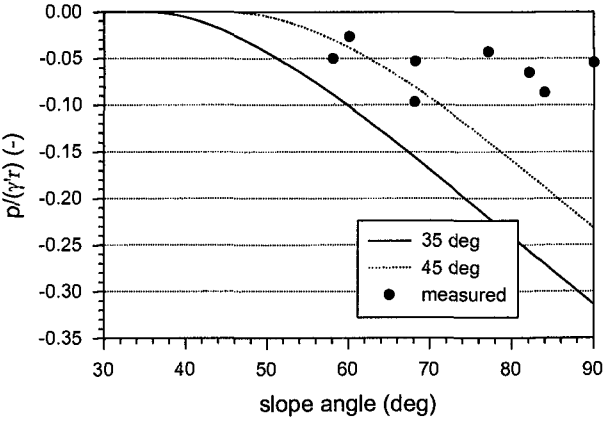

Figure13: Measured pore pressure reduction compared with theory.

Conclusions

Measured pore pressure reduction in the sand is caused by groundwater flow to the limited zone of dilatant sand.

The slope angle developing during the suction of sand and therefore the maximum forward velocity and hence production does not only depend on the sand characteristics. Also the height of the breach as well the effect of the density current are of importance. At a high breach this can lead to very small slope angles, and even to unstable breaching. This effect has been reported in literature from field experience and has now been proved by experiments and theory.

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