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Groot de, M. B.; Mastbergen, D. R.

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M.B. de |Groot*, and D.R Mastbergen**
* GeoDelft, Delft, the Netherlands
** WL|Delft Hydraulics, Delft, the Netherlands

The development of a scour hole and in particular its upstream slope is determined by several morphological and geotechnical processes. Simple sliding and liquefaction flow slides are traditionally considered to be responsible for any slope instability. The process of breaching and slope erosion by density current was only recently recognised as another potentially important process. Its relevance for the stability of scour hole slopes is discussed in this paper.

I. Introduction

Scour holes near bridge piers, sluices, barriers and other structures in sandy rivers and estuaries may endanger the structure stability. A bed protection is usually required to protect the sand against the most turbulent flow and to keep the scouring far away from the structure (Figure 1).

Dimensioning of the bed protection requires the answer to such questions as:

- What reduction of scour hole depth, D, and slope angle, β, are caused by increasing the length, L, of the bed protection?
- What value of β and value of D guarantee the slope to remain stable in case of dense sand? Idem in case of loose sand?
- What length, L, need to be chosen to guarantee that the structure foundation remains stable in the unhoped case that slope instability occurs?

The answers require knowledge of the physical processes. Traditionally only morphological processes are considered to be relevant for the answer to the first question and only geotechnical processes for the other questions. Recently, however, a combination of partly morphological and geotechnical processes was recognized to play an important role in slope instability: breaching and the successive erosion by a sand-water mixture density or turbidity current that is produced by a breach [1, 10].

The consequences of this combination of processes for the design of bed protections will be discussed and illustrated with the design for the Oosterschelde barrier.

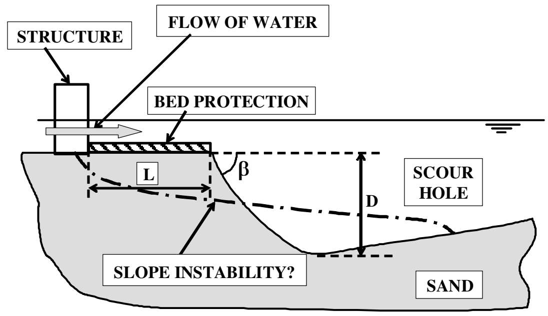

Figure 1. Dimensioning bed protection in view of scour hole

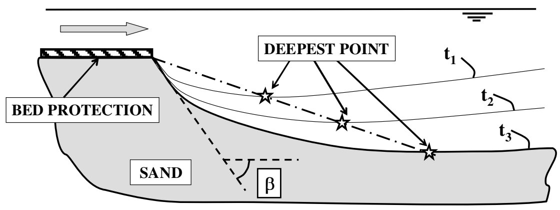

Figure 2. Scour hole shape is constant during increase of scour hole depth.

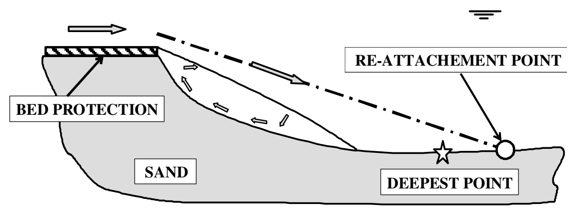

Figure 3. Flow pattern in scour hole

II. Physical processes

A. *Scouring*

The development of a scour hole is largely determined by erosion, which is a purely morphological process. A general description is presented by Pilarczyk in [2]. The deceleration of the flow after passage of the structure goes along with large velocity gradients and the development of additional turbulence. Thus, the downstream flow has a much larger sand transport capacity than the upstream flow and causes erosion of the bed as soon as the flow passes over the unprotected sand bed.

Four phases of scour hole development can be distinguished: initiation, development, stabilization and equilibrium. The second phase, which may take many years, is of special importance for design. The scour hole depth increases rapidly in the beginning of this phase and more slowly in course of time. The scour hole shape, however, remains nearly unchanged: the deepest point remains on the same line through the end of the bed protection and the upstream slope angle, β, remains constant (Figure 2).

The flow pattern remains the same as well: detachment of the flow at the end of the bed protection, a main stream similar to a jet type flow [3] and re-attachment close to the deepest point of the scour hole, where most of the scour occurs (Figure 3). The moderate upward flow in the wake causes also some scour along the lower part of the upstream slope. The scour along the higher part of this slope is very limited.

The larger the flow velocity at the end of the bed protection the higher the speed of scouring. A similar influence has the turbulence at the end of the bed protection. This turbulence, however, has also another effect: the larger the turbulence the steeper the upstream slope of the scour hole, β.

A relationship between a turbulence parameter and β has been found by systematic scale model investigation. See section 2.4.9.7 of [2]. The scaling had been performed with polystyreen grains with such dimensions and under water weight that conformity could be approximated with respect to the most important morphological aspects: flow pattern, fall velocity of the grains and angle of repose. However, the approximation was not completely satisfactory and conformity with respect to geotechnical soil properties such as angle of shearing resistance and dilatancy is uncertain, whereas certainly no conformity had been arrived with respect to the permeability of the modelled sand.

Comparison between full scale and small scale tests with high turbulence [3] made clear that the average value of β along the bed protection edge found in the full scale tests agreed well with the value found in the small scale tests, but that the slope was significantly steeper at some locations, resulting in several slope instabilities.

The full scale tests illustrated another limitation of scale tests: natural soil usually consists of layers, some of which may be cohesive and cause a significant temporal delay of the scouring process.

Finally, the question may be raised whether the development of a scour hole, and in particular the steepest slopes, may also be influenced by the process of breaching and slope erosion by density current (see below under D). If so, this process will be underestimated in any scale model. Indeed the sand properties responsible for any process of breaching and the generation of an erosive turbidity current are not modelled correctly in the scale model

B. Simple sliding as cause of slope instability

A simple undeep sliding occurs as soon as the upstream slope in non-cohesive soil becomes steeper than the slope corresponding to the angle of shearing resistance, i.e. a slope of $\beta \approx 30^\circ$. Sliding with more complicated rupture surfaces may occur if cohesive layers are present. The shear strength in natural cohesive soils is nearly everywhere sufficient, however, to avoid sliding when the slope is more gentle than 1 : 2.

Temporarily steeper slopes, up to vertical, may be present in the case of shear in densely packed sand due to dilatancy. In that case temporary negative pore pressures will occur in the sand body with inflow of water from outside into the soil. This will be discussed under ‘breaching’ below.

C. Liquefaction flow slide

Loose sand has the tendency to contract, i.e. to decrease in volume during shear. Pore water flow resists such decrease, in case the sand is saturated and undrained and excess pore water pressures arise, causing a decrease in effective stress and in shear strength. This may be called liquefaction or, at least, partial liquefaction.

Some results of undrained, strain controlled Direct Simple Shear test on saturated sand samples are schematised in Figure 4. The test on medium dense sand shows a gradually increasing shear stress, τ, with increasing shear strain, γ. The test on loose sand, however, shows decrease in shear stress after the shear strain has reached a certain value. This decrease corresponds to a significant increase in excess pore water pressure to a value higher than 50% of the vertical stress σ_v, which means that the sand may be called (partially) liquefied.

The point where the shear stress starts to decrease may be called a point of ‘meta-stability’. This means that any very small load change would lead to a sudden collapse of the sample (at least a very large shear deformation and sudden large increase in pore pressure) when the shear stress has reached this value in a stress-controlled test.

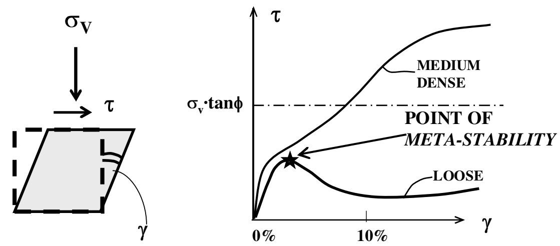

Figure 4. Result of direct simple shear test on undrained saturated sand

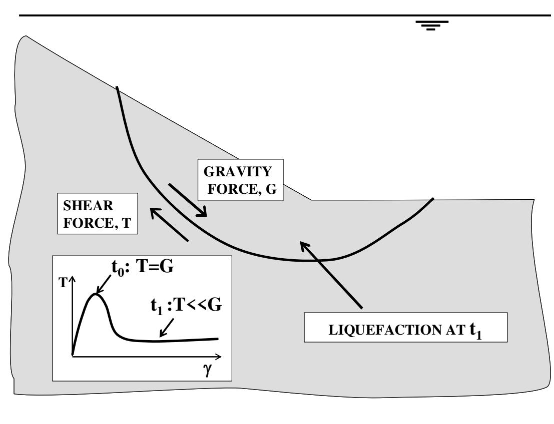

Figure 5. Liquefaction flow slide in case of meta-stable sand

A large part of the sand mass underneath a slope may be in a similar state of meta-stability (Figure 5) if the sand is loose and fine enough and if the slope is steep and high enough [5]. The sand in a slope at such location experiences monotonic shear loading due to gravity and the corresponding shear deformation does not yield any reduction of the loading. Consequently the sand is in a similar situation as in a stress controlled shear test. Much of the sand is in a nearly undrained condition if the sand mass is large enough, e.g. because the slope is relatively high, and if the sand is fine enough to have a relative low permeability.

Then any small change in loading, e.g. by a local erosion or a sudden decrease in water level, may disturb this meta-stability and cause the collapse of the sand mass, characterised by large excess pore pressures: the sand is 'liquefied' and starts to flow.

The sand is not completely undrained and some pore water is expelled, whereas the excess pore pressure reduces to zero when the sand has contracted enough. Then the sand flow stops as well [6]. The time needed for this process depends on the permeability of the sand and the thickness of the liquefied layer. The lower the permeability and the larger the thickness, the longer takes the liquefaction flow slide and the larger is the resulting slope deformation.

D. Breaching and slope erosion by density current

No liquefaction flow slide is to be expected in dense or medium dense sand. Slope instability may occur by 'simple sliding', but also by the combination of breaching and the erosion due to the sand-water mixture density current that is produced by the breach [1, 8].

A breach is a steep superficial sand slope disturbance that gradually retrogrades upward along the slope with the so-called wall velocity, defined by permeability and porosity of the sand bed. The slope of the breach is so steep that no long-time equilibrium is possible (Figure 6). Gravity induces a shear deformation of the sand at the breach surface. The tendency to dilate causes the development of negative excess pore water pressures at a small distance from the breach surface, where the sand behaves semi-undrained. The negative pore water pressures induce a temporary increase in shear strength of the sand, which keeps the sand stable for some time.

The negative pore water pressures cause an influx of water into the pores yielding an increase in pore volume of the sand. As soon as the pore volume has increased enough and the negative pore pressures have nearly disappeared, failure occurs and the grains fall downwards along the slope surface, resulting in the retrogression of the breach. The falling sand grains mix with the water outside the soil which is called entrainment.

Dependent on the height and the retrogression velocity of the breach, the initial flow velocity may be sufficient to keep the sand grains suspended and the breaching process results in a turbulent sand-water mixture flow at the toe of the breach. This mixture flows downward as a density current. Dependent on slope angle and height the density current will accelerate or decelerate.

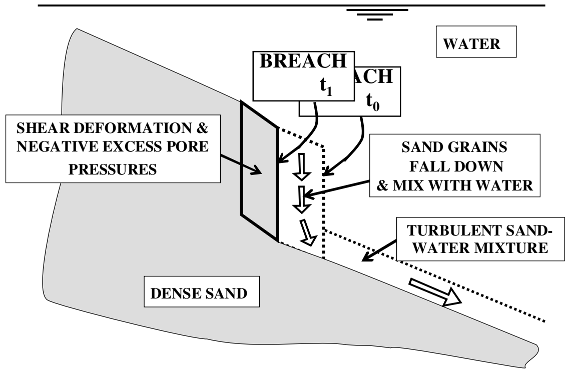

Figure 6. Gradual upward movement of breach and resulting sand water mixture

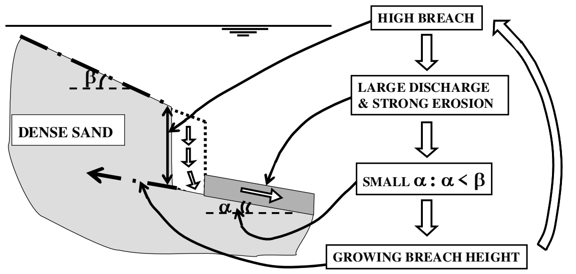

Figure 7. 'Ignitive' breach growth if initial breach height is larger than critical value

Erosion and sedimentation take place at the interface of the flow with the sand bed. Sedimentation dominates if the flow velocity of the density current is relatively small, due to a gentle slope of the sand bed or if the sand is particularly coarse. Erosion dominates, however, if the slope is steep enough and the sand relatively fine. Due to the increasing density and sand transport rate the flow velocity will increase further, resulting in even more erosion A so-called ignitive or self-accelerating turbidity current has developed (Figure 7). All the eroded sand will be transported downward and meanwhile the breach will retrograde upward until the original estuary bed with the bed protection has been reached. This breaching process is generally recognized as a slope failure or slope instability during or after dredging in sand pits and in submarine canyons [1, 8].

The minimum required time to establish a fully developed flow over the full slope height is defined by the breach retrogression or wall velocity and the slope height and is generally several hours.

The conditions for establishment of an erosive self-accelerating sand-water mixture flow resulting in a slope instability therefore are in the first place a steep sand slope and sufficient slope height in relation to the sand properties and an initiating event creating a breach which is high enough to suspend the sand. Moreover, a necessary condition to maintain the erosive flow and slope retrogression is the transport rate of the sand transported to the toe of the slope. Elsewhere, the sand will settle eventually and a gentle slope will be created on which the flow will gradually extinguish.

The question needs to be considered under what circumstances these conditions can be met in a scour hole. The first condition, a relatively steep slope, β, can be present with large turbulence at the downstream end of the bed, as discussed above. A slope of 1:3 over 5 m or more is certainly steep enough for sand of about 200-300 μm, according to computations and field observations [1, 8]. The second condition, the initiation of a relatively high breach, however, requires a special composition of the subsoil and the interaction with other processes, as will be discussed below. The third condition, the transport rate of the sand at the toe can be provided by flow of the sand into deeper parts down slope or pick up by the main flow in the zone of flow re-attachment (Figure 3).

E. Interaction of processes: conditions for breaching slope instability

Slope instability due to a strong erosive breach induced self-accelerating turbidity current requires an initial high breach, i.e. the presence at any moment during the scouring process of a significant part of the slope that is so steep that it is only temporarily stable. The breach will not be very high during the normal scour hole development process if the subsoil consists of homogeneous (medium) dense sand. Then the scour hole shape develops regularly as illustrated in Figure 2, although some minor bank retrogression and bed protection damage is expected .

The presence of a clay layer, however, may bring about a more irregular scouring process. The layer may temporarily keep up a steep part of the slope. After undermining of the layer it may break off and cause a high breach in the sand above (Figure 8). An additional effect of the sudden sliding in clay and sand is the large increase in sand transport rate. Although this large transport rate does not continue for a long time, it may be sufficient to cause a strong local erosion process just below the slide due to a self-accelerating density current and initiate a retrogressive breaching process.

The presence of a layer of loose sand may cause a local flow slide and a subsequent breaching process (Figure 9) with a similar slope development.

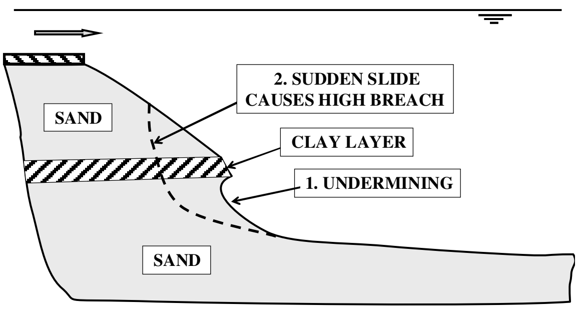

Figure 8. Clay layer as condition for high initial breach

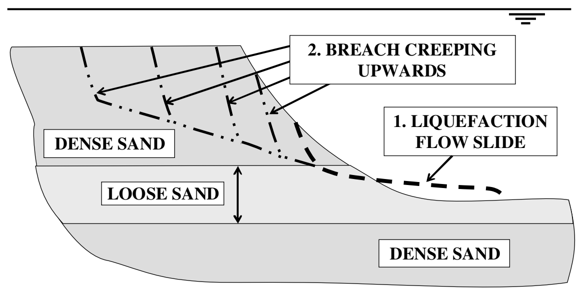

Figure 9. 'Ignitive' breach growth after liquefaction flow in layer of loose sand

III. REVISION NEEDED OF TRADITIONAL DESIGN PROCEDURE?

The 'traditional' design procedure is described in [2]. Two requirements could be formulated for a safe design:

1. The scour hole slopes should remain stable according to the best prediction method
2. If a slope instability occurs nevertheless, it should not endanger the structure

Both requirements can be reached by making the bed protection long enough. The longer the bed protection the less turbulence at its downstream end, which has two positive effects: the upstream slope angle, β, remains small, a guarantee against slope instability and the scour hole depth remains limited, a guarantee for the second requirement.

In case of loose sand and the risk of a liquefaction flow slide, however, an extremely long bed protection might be needed to meet both requirements and other measures could be considered, as discussed below for the example of the for the Oosterschelde barrier.

According to the traditional design procedure only the mechanism of simple sliding endangers slope stability if no loose sand is present. This would mean that slope instability could only occur in slopes steeper than 1 : 2 and any slope instability would not endanger the structure if the bed protection length is slightly longer than the expected scour hole depth.

Another traditional assumption, in case of a loose sand layer of limited thickness, was that the slope resulting after an instability would only be gentle at the level of this layer and would remain steep in other layers.

Slope instability due to breaching and erosion through density current was not considered. This is an omission and the following revision of the design procedure seems to be justified:

- Consider the risk of breaching and erosion in case of non-homogeneous subsoil. Compute the expected slope development given sand properties and expected scour hole depth.
- Estimate the geometric characteristics of local slides resulting after erosion near clay- or silt layers and in particular the resulting initial

breach height and the resulting temporary soil transport rate
- Estimate the geometry resulting after a local liquefaction flow slide in case of the presence of a loose sand layer amidst more dense sand layers and in particular the resulting initial breach height
- Predict the slope that results after the above predicted initial breach height or temporary soil transport rate due to the process of breaching and erosion through a density current.

IV. Example of Oosterschelde barrier

The Oosterschelde is a sandy estuary of around 80 km^2 of high ecological value. A barrier with gates was constructed in the mouth to guarantee the safety of the surrounding land against flooding in the early 1980's. The gates are closed only in case of extreme high water in order to keep the tidal variation during most of the time. The barrier has been designed such that the tidal variation is now 80% of the original variation. This could be reached by reducing the flow opening to about 20% of the original opening of the open Oosterschelde.

The flow opening with gates has been concentrated in the three largest estuary channels The flow opening reduction causes flow velocities in the opening of the barrier which are roughly 4 to 5 times the flow velocities up- and downstream the barrier. This causes a significant increase in turbulence downstream of the barrier in these three channels. This has resulted in 6 large scour holes, 3 on the estuary side (flood) and 3 on the sea side (ebb) downstream of the bed protection. The design with respect to the bed protection length and the scour holes is described in [7] .

The estuary side scour hole in the largest channel will be considered in more detail. The original depth in the 1 km wide central part of the channel varies from 40 m in the South to 25 m in the North. A channel bed protection until 650 m outside the axis of the barrier was placed before the construction of the actual barrier. The speed of scouring at the estuary side of this bed protection edge increased significantly after the start of this construction..

Scale modelling for these bed protections resulted in a prediction of the scour hole shape which can be characterised in the direction parallel to the bed protection edge by two deep parts, one in the South of the central channel part and the other in the North [8]. The predicted shape in the flow direction can be characterised (Figure 2) by tan β = 1 : 2 and the deepest point at 1 : 4 from the bed protection edge at the location of these deepest parts of the scour hole. More gentle slopes were expected in between. Inspection of the present scour hole shows that these predictions were quite correct.

The predicted depth in the two deep parts of the scour holes was roughly the same, but it was considered to be rather uncertain in view of a number of uncertainties in the boundary conditions and the model uncertainty. The predicted depth varied between 30 m and 80 m for the year 2004, roughly 20 years after the start of the barrier construction. Now, the most optimistic prediction appears to be correct for the Northern deepest part, where a depth of 30 m was measured in 2004, and appears to be even too pessimistic in the Southern part, where a depth of 20 m was observed.

The risk of liquefaction flow slides was analysed extensively as most of the sand in the subsoil above the level 30 m below mean sea level is loose [7 and 8]. A typical flow slide starting in the upstream slope would destroy the bed protection over a length of approximately 2 times to 5 times the scour hole depth. The risk analysis made clear that special measures were needed to reduce the risk. Two measures were applied:
- compaction of the sand underneath the downstream edges of the bed protections as illustrated in Figure 2.4.9.11 of [2]
- fixing by means of stone dumping of the upstream scour hole slope as soon as it had reached a certain slope angle, β, over a certain height (Figure 10).

The first 30 m to 60 m of stone dumping was accomplished before completion of the barrier. The area of the stone dumping reaches now more than 100 m from the edge of the bed protection close to the deepest part of the scour hole.

The measures appear successful: no damage to the original bed protection was observed up to now. The need for such measures seems to be illustrated by a very large failure of the Northern side slope of the scour hole which occurred just outside the bed protection between early 2004 and early 2005. The profiles before and after the slope failure are sketched in Figure 11.

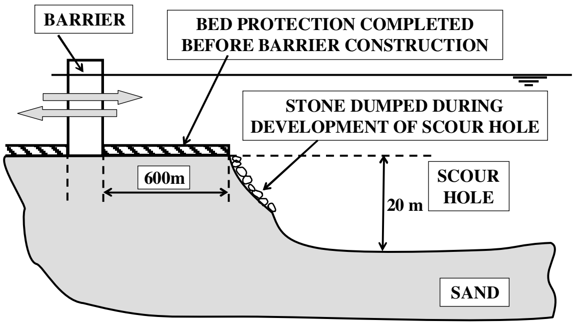

Figure 10. Design Oosterschelde Barrier

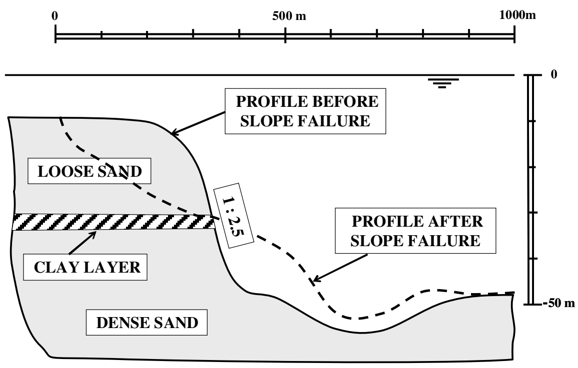

Figure 11. Slope failure in side slope of Oosterschelde scour hole

The situation just before the slide looks similar to the one sketched in Figure 8 and the question is raised whether the slope development in the sand above the clay layer may have been determined by breaching and slope erosion by density current. There seems to be one important difference: this sand was rather loose with the tendency to contract, rather than dilate, whereas breaching requires dilative sand. Nevertheless, if sand is not extremely loose, it shows some dilation after the contraction, which might enable breaching. This is assumption is made for the Oosterschelde sand above the clay layer in order to investigate, by means of calculations, if breaching may have been the cause for the observed slope development in the top 20 m of the upstream scour hole slope.

Therefore it is assumed that the subsoil consists of dominantly moderately packed fine sand of 200 µm, interrupted by a thin clay layer or by a 3 m thick layer of loose sand at a depth of 20 m underneath the original estuary bed as shown in Figure 11.

Then, an 'initial' breach with a height of about 3 m could have occurred after so much scouring that the scour hole was more than 20 m deep. Calculation of the process of breaching and erosion through density current results in the profiles given in Figure 12. The computed profiles represent the stationary retrograding situation when all the sand eroded from the slope is transported downstream into the scour hole or tidal current. Besides the sand properties the sand transport rate at the toe, which is active during at least several hours after initiation, determines the slope development and the retrogression rate. The larger the rate, the more gentle the resulting slope. If the sand is not transported at the toe sufficiently it will accumulate and the breaching process will gradually stop. The transport rate is estimated to be 15 to 60, kg/ms.

For comparison a slope of 1:2.5 and a slope of 1:10 are given in Figure 12. It can be concluded that due to the breaching process a maximum bank regression of about 100 to 300 m can be expected. The slope is steep at the top and very gentle just above the clay layer at a depth of 20 m below the original 'sea' bed.

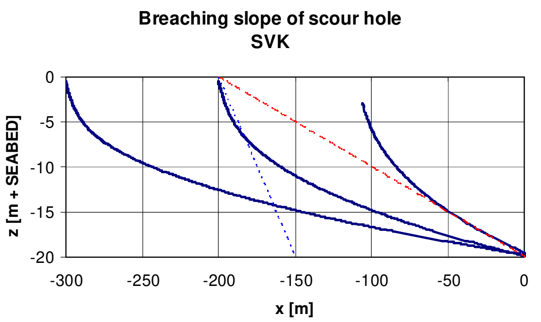

Figure 12. Computed slope development in the loose sand above the clay layer of Figure 11, assuming breaching in 200 µm sand for sand transport rate of respectively 60, 30 and 15 kg/sm

V. Conclusions

Only erosion, a purely morphological process, is usually considered to be responsible for the development of a scour hole, as long as no clear slope instabilities occur. The possibility should be considered, however, that the gradual development of the upstream scour hole slope is partly determined by breaching and erosion by a sand-water mixture density current.

Instability of the upstream scour hole slope is determined by mainly geotechnical processes in case of a subsoil of homogeneous sand. If densely packed the stability is determined by simple sliding; if loosely packed by liquefaction flow sliding.

In many cases, however, the subsoil is inhomogeneous: layers of densely packed sand are interrupted by layers of clay or loosely packed sand. Then, the slope instability may be determined by a combination of geotechnical instability and breaching with erosion by density current, resulting in a considerable bank regression.

This illustrated by a hindcast of a very large slope failure observed in the inhomogeneous soil adjacent to a scour hole near the Oosterschelde Barrier.

The measures taken to avoid slope failure of the upstream slope of the Oosterschelde Barrier scour holes appeared to be successful up to now. The failure observed in the side slope illustrates the need for such measures.

Acknowledgment

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