CHAPTER 241

Engineering Approach to Coastal Flow Slides

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Abstract

Flow slides can play an important role in the stability of coastal foreshores and structures, in harbour design, in dredging activities and placing of hydraulic fill structures. In the south western part of the Netherlands the phenomenon is of major concern for the protection against flooding by means of dikes. More than 1100 slides have been registered since the year 1800. In the paper the practical experience and the knowledge obtained from experiments and fundamental research is briefly summarized. An engineering approach to coastal flow slides that combines the Dutch experience with flow slides with results of fundamental research of the past 10 years, is described.

Introduction

It is now 45 years ago that Koppejan et al [1948] first published on the subject of coastal flow slides in the Netherlands. The major concern at that time was that parts of the sandy foreshore in the Dutch province of Zeeland, sometimes including parts of the dike or the entire dike body, suddenly liquefied and disappeared into deeper water. Figure 1 is an example of such an event along the shore of the Eastern Scheldt basin. These events were called flow slides, as the loosely packed sand, apparently without reason, lost its

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stability and moved like a highly concentrated sand-water mixture. The major slides involved a tremendous quantity of sand, leaving behind very gentle final slopes.

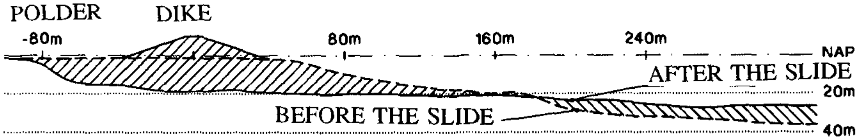

Figure 1 Example of an actual flow slide along the shore of the Eastern Scheldt basin (Leendert Abrahampolder)

Flow slides can play an important role in the stability of coastal foreshores and structures, in harbour design, in dredging activities and placing of hydraulic fill structures. This paper deals with practical aspects of the phenomenon of flow slides. In many situations the chance that a flow slide will occur is negligible, but at the same time there is a need for practical tools to judge this risk. An engineering approach to coastal flow slides is presented that combines the Dutch experience with flow slides with results of fundamental research of the past 10 years.

Description of flow slides

A flow slide can be described as an instability that occurs in a fairly gentle underwater slope consisting of loose sand, causing liquefied sand to flow out into an even more gentle slope. A flow slide may occur after a change in slope geometry, for example steepening and/or deepening of the channel as a result of scour. A rather small, but quick change in load may trigger the sudden liquefaction of a vast amount of sand, which subsequently flows down the slope (Kramer 1988). In many cases the triggering mechanism is not known. It is thought flow slides can be triggered by almost any small change in soil stresses, caused by for instance seepage due to tidal water level variation, vibrations, ship waves, and so on. Consequently, if the conditions in the subsoil required for liquefaction are present, it is of no great importance what exactly initiates a flow slide.

Flow slides also occur in other parts of the world, for instance along the banks of the Mississippi river (Torrey, 1994), along the slopes of artificial sand islands in the Beaufort Sea (Sladen et alii 1985). The risk of flow slides is also present during dredging works in loose sand, unless special preventive measures are taken.

If a loosely packed sand is loaded by applying a small shear stress the sand will tend to reduce in volume. If the pores between the grains are water saturated either water will have to flow out of the pores, or the water will have to be elastically compressed to effect this change in volume. If no water can flow out (undrained conditions) an excess pore pressure will be the result.

Excess pore pressure reduces the effective pressure, and with that, the shear strength of the soil. If the sand is present in an underwater slope this can result in slope failure. This slope failure may take the form of a small slip failure but if conditions are unfavourable enough this may develop into a full size flow slide. In our opinion, liquefaction often first starts near the toe of the slope. A sudden loss of stability at the toe leads to a retrogressive failure of the entire slope.

Dutch experience

Flow slides are encountered in many parts of the world. The Dutch experience is largely limited to the estuaries in the South Western part of the Netherlands, and in some cases in harbours or sand gain pits elsewhere. Since 1800 records of flow slides and slip failures along the shores of the Province of Zeeland have been kept (Wilderom, 1979). Between 1881 and 1946 229 flow slides were registered, resulting in a total area lost of 660 acres and a displaced volume of 25 million m^3 (Koppejan et al, 1948). The material displaced during one single slide can amount up to 5 million m^3 and a recession of the shore line up to 400 m. On several occasions stretches of dike of several hundreds metres width were lost. Of a total of 1129 slides that have been registered between 1800 and 1979 a number of 200 were sufficiently documented to make further analysis possible. This has lead to practical criteria for the occurrence of flow slides under Dutch circumstances. Among these conditions is the assumption that flow slides are mostly found in young holocene marine sediments. Local experience shows that older holocene deposits and pleistocene deposits are less susceptible to flow slides. This emperical rule may be subject to local conditions. In Zeeland the pleistocene deposits are often densely packed. The older holocene deposits can be deposited more slowly than the younger holocene deposits, resulting in a denser package of the material. In case of the older deposits also bonding effects may play a role. There may also be an influence of difference in stress history between the deposits. These factors can be different for other locations however.

One of the most important geometrical factors is the initial slope along the channel. Figure 2 shows the average slope inclination before the occurrence of more than 100 field flow slides (squares) as a function of total slope height or channel depth. Much scatter is found and a useful tendency can not be deduced from this graph. A reasonable explanation is that the scatter is primarily caused by differences in local circumstances among which different sand properties and different in-situ densities. Apart from that, the average slope angle is probably not the best measure for evaluating the flow slide susceptibility. It stands to reason that the inclination of the steepest part of the slope may be a better measure.

In Figure 3 therefore, instead of the average slope, the inclination of the steepest part of the slope is shown, again as a function of slope height for the more than 100 locations where flow slides occurred in the past. The idea is that

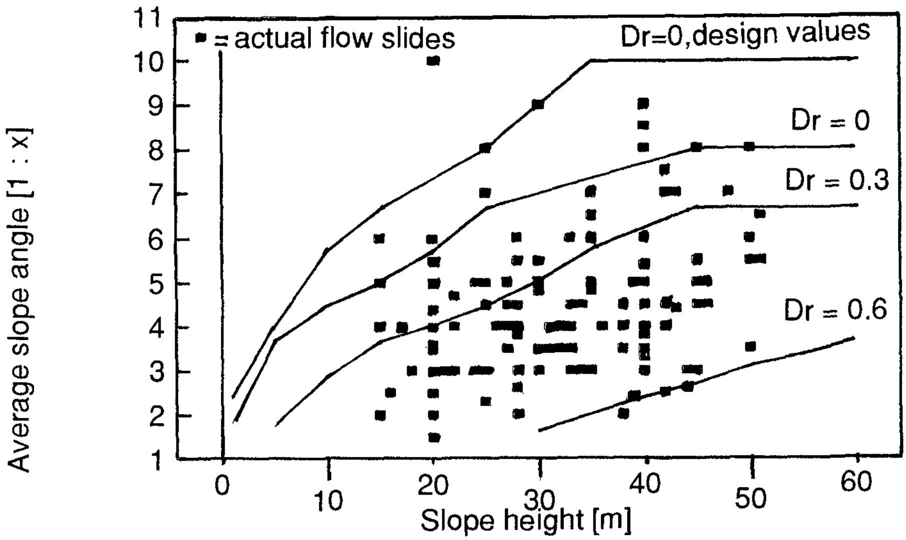

Figure 2 Actual flow slides compared to model results: Average slope angle before the slide as a function of slope height

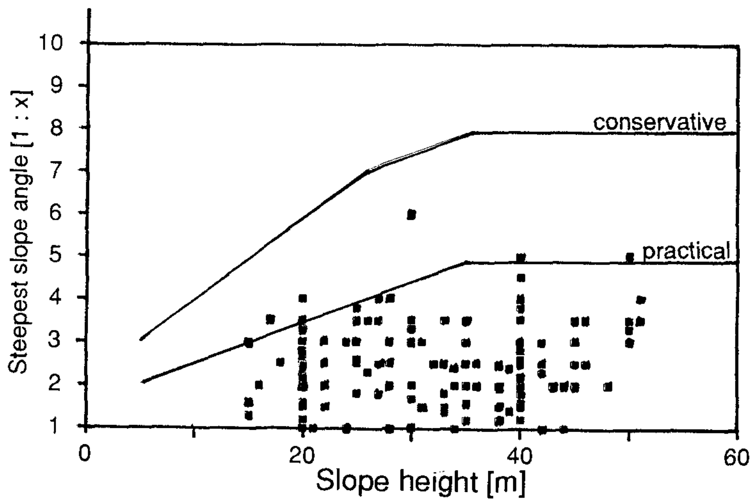

Figure 3 Actual flow slides compared to model results: Slope angle of steepest part of the slope as a function of slope height

steepening due to scour will be most dangerous in the steepest part of the slope. The height of the steepest part varies between a few metres to about 30 m. Although a somewhat better result is found, the scatter remains rather dominant. Practical criteria for the initial slope inclination at which flow slides may take place, derived from the geometrical information gathered in Fig. 2 and 3, will be very uncertain if applied to a specific location and a large safety margin should be included. On the other hand the available data of flow slides in the field makes it possible to get a rough impression of the flow slide probability. Therefore the total number of slides within the period of the last 100 years combined with the total stretch of dikes and foreshore principally vulnerable for flow slides and the geometric data of the flow slide records are analysed thoroughly. Moreover the average chance that not only the foreshore is affected, but also dike failure takes place, in relation to the locally present foreshore length can be assessed too by using the available information concerning final slopes after occurrence of the slides. Although very useful in Dutch engineering practice, again this statistic result has to be treated very carefully if applied to a specific site where local geotechnical information is absent.

Measures against flow slides

In past centuries no measures against the effects of flow slides along the foreshore were taken. The occurence of dike falls was simply taken for granted. Secondary dikes were built behind the sea dike to keep the area of inundation limited. Since 1880, due to increased application of stone protection, in more and more stretches the recession of the shore line has been stopped. The number of flow slides and slip failures has reduced accordingly. The effectivity of shore protection in regard to the prevention of flow slides is not due to a reduction of flow slide susceptibility of the sand. Instead, fixing the foreshore makes steeper slopes impossible. The observations that flow slide occurrence was stopped after slope fixation confirmed the theory that in addition to sand properties and actual slope steepness, also change in geometry (e.g. steepening of the slope) is an important conditional factor for the occurrence of flow slides.

Another method, consisting of the application of groyns to arrive at a system of 'fixed points', was less succesfull. Although the objective of keeping the tidal channel away from the dike could be realized by this system, local scour caused slides near the tip of the groyns, causing the system to fail.

The risk of flow slides can be reduced by densification. Experiments using different densification techniques have been carried out in the Netherlands. The succes of different techniques depends on material properties such as the amount of fines. Also, densification has to possible up to a certain depth to be effective. In the Netherlands, one example of large scale densification is known. The subsoil of the Storm Surge Barrier in the Eastern Scheldt was densified, using a specially developed densification ship, the

Nautilus. With large vibratory needles, densification up to a depth of 30 metres could be realised. In most cases however, densification is not economically feasible.

Experiments

Flow slides are seldomly witnessed, and then of course only surface events can be seen. Witness reports of flow slides indicate that the proces can take several hours, during which at the surface sandmasses of one metre thick by several metres width slide down into the water. The retrogression speed is several metres per hour. There are also indications that under water the flow of sand and water is much quicker, in the order of metres per second. A fine opportunity to study flow slides were large scale tests on hydraulic fill in 1988 (Bezuijen and Mastbergen, 1988). During the test series sand bodies were constructed with varying deposition rates in a test flume of 2,5 m height. Especially the tests with fine sand (D_{50} of 135 μm) showed that flow slides were of major influence on the final slope angle. Tests with a coarser sand (D_{50} of 225 μm) showed considerably less flow slide susceptibility, resulting in steeper slope angles. Another remarkable result of these tests was the fact that slope height was very important. The sand body could develop to a height of 1 to 1,5 m before a flow slide took place, after which the same cycle started again. Pore pressure measurements showed that liquefaction occurred very sudden: pore pressures rose from zero to values indicating almost complete liquefaction within 0,1 seconds. After that the actual slide and the dissipation of pore pressures could last approximately one minute. The sand body of course was of limited dimensions, which can implicate that with increasing dimensions also the time scale in which events take place will be larger.

Other interesting large scale experiments were carried out between 1973 and 1976 (Kroezen et al, 1982). During these tests a loosely packed and water saturated sand body of 2.5 m high, 3 m wide and 25 m long was forced to liquefy at the fairly steep slope at one end of the mass consisting of fine sand. After that a retrogressive failure mechanism could be witnessed that displaced with a horizontal speed of 0.5 to 1.5 m per second through the sand body. In some tests the retrogressive failure almost reached the other end of the facility at 25 m distance of the location where the mechanism was initiated. Very gentle final slopes were found (up to 1 to 25). During the passage of the failure front excess pore pressures almost equal to the initial effective stress in the sand were measured, indicating that full liquefaction had taken place.

Research

In 1981 fundamental research was started. By that time liquefaction could be understood in terms of critical density, as defined by the results of drained and undrained triaxial tests on soil samples (Lindenberg and Koning, 1981). Since then progress has been made in two aspects. First, it has been attempted succesfully to describe the constitutive behaviour of loosely packed sands, based on the results of drained triaxial tests. On the one hand there is contraction, caused by shear stress, which results in excess pore pressure if no drainage can take place. Excess pore pressure in its turn leads to decompression. These two volumetric aspects can be measured seperately in drained triaxial tests. If the behaviour of the soil is undrained, such as is the case in liquefaction problems, the tendency to contract and the tendency to increase in volume due to excess pore pressure have to compensate each other. Models that take these aspects in regard have proven to be succesfull in describing the response and failure of loosely packed sand in triaxial tests.

In underwater slopes in nature, shear stress is related to the foreshore geometry. Slope height and slope angle have influence on in-situ stresses. A research programma was started in 1985 to study the influence of slope geometry. A mathematical model has been developed in which the effects of sand properties and geometry characteristics were combined. The in-situ stresses for a given geometry are given by analytical formulae, obtained by generalizing the results of Finite Element computations.
These in-situ stresses are introduced in the liquefaction model together with the basic relevant constitutive behaviour of the sand as a function of sand density.

The model itself verifies for 500 points in the sand mass the so called instability criterion during an incremental slope steepening under undrained conditions (Stoutjesdijk, 1993):

$$d\gamma = 1/\lambda \,.\, d\tau_{xy}$$

λ = stability factor
$d\gamma$ = incremental change in shear strain
$d\tau_{xy}$ = incremental change in shear stress

λ is in fact the eigenvalue of a matrix system comprising the entire system of stress strain relations for the sand for given sand density.
Instability occurs if $\lambda < 0$. It means that an increase in shear strain can only be attended by a decrease in shear stress. Because slope steepening is generally accompanied by shear stress increase, the condition $\lambda < 0$ in fact indicates that large shear deformation will take place. The instability condition has been assumed identical to liquefaction.

Because the stress state as well as the sand behaviour varies from point to point, and with slope angle and slope height, instability will start in one point in the sand mass for a certain slope angle. The corresponding slope is the critical slope inclination for the considered foreshore. As the slope steepening in the calculation proceeds, the unstable zone will grow. An extensive series of calculations has shown that the most critical zone in most cases is located next to or just below the toe of the slope. In Figure 4 the result of a calculation is shown. The figure shows several contourlines. Inside each area, defined by a contourline, instability has occurred during the calculation for a certain slope angle. The most inner contourline gives the critical slope inclination, in this case 1 : 4.5 (tanα = 0.222). The critical zone, as can be seen in Figure 4, is situated near the toe of the slope at some depth beneath the toe.

In the liquefaction model only two slope shapes can be introduced and the sand properties refer to one sand density for the entire mass. For practical purposes the properties of the most susceptible layer will be introduced in the model. This sandlayer only has to be considered critical when the calculated unstable zone has reached the layer boundary. The corresponding slope inclination is the critical inclination for that most sensitive layer. In case a second layer could be susceptible too, the calculation has to repeated with the sand properties for that layer. In this way the stability of a foreshore can be assessed.

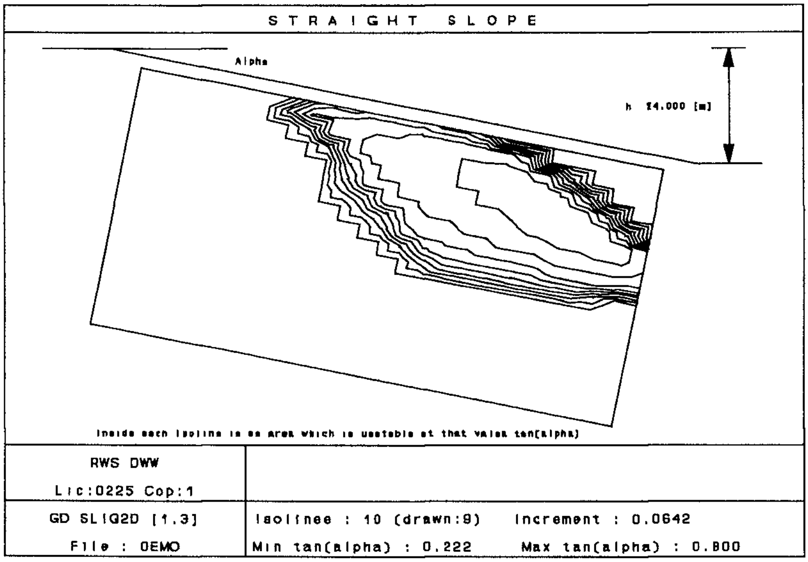

Figure 4 Example of a calculation result with the model. Note the situation of the critical zone inside the inner contourline.

Verification

The research results have lead to a model for the prediction of flow slides. In the model slope height, slope angle and (material behaviour as a function of) relative density are the most important factors. The model has been verified on a number of flow slides, that have taken place in the past. Also the trend following from some 150 actual flow slides as shown in Fig. 2 and Fig. 3

can be compared with the results of model calculations. Average values for the input parameters have been used. Calculations were made for several slope heights and several relative densities. Relative density is defined here as Dr = (nmax - n)/(nmax - nmin), in which n, nmax and nmin are the in-situ density, the maximum density and the minimum density. Fig. 2 and 3 show that most actual slides can be represented by relative densities between 0 and 0.6. Another important trend is the influence of the slope height or channel depth. The calculation results in Fig. 2 and 3 indicate that a flow slide may occur at a much more gentle slope in case of deeper channels. This effect is the logical consequence of the basic stress strain relations for sand, found from triaxial tests in the laboratory and introduced in the model.

Practical approach

To make a prediction of the flow slide susceptibility for any particular situation with the flow slide model it is necessary to perform in-situ borings, in-situ density measurements, triaxial tests, calculations and analysis. For many practical applications this may either take too much time or may be too expensive. A set of calculations has been performed, based on Dutch sands and applicable to comparable situations only (similar material, tidal range 3 to 5 m). Unfavourable assumptions have been used to be on the safe side. The result is shown in Fig. 2 as the line marked "Dr=0, design values". In many cases information on local circumstances may lead to a less conservative result.

It is possible to derive an impression concerning the type of material and the in-situ density from cone penetration tests (CPT's). Probably, because of the relatively static character of this test, the CPT yields a better impression of in-situ density than more dynamic tests such as the widely used Standard Penetration Test (SPT's). A second advantage of the CPT is that a continuous image of the subsoil is obtained.

If the investigation is further pursued, then an extensive programme of field tests, laboratory tests and calculations has to be performed. Because of the size and the cost of these activities, it has to be considered whether or not the chance that the investigation will lead to limitation of preventive measures is present. The investagation consists of electrical density measurements, borings, sieve curve analysis, determination of maximum and minimum densities, triaxial testing and calculations with the flow slide model. This entire programme is necessary because the flow slide susceptibility of one particular situation can only be determined if detailed information on in-situ density and behaviour of the material of the site is available.

Uncertainties are introduced with each step of the procedure. These uncertainties can be quantified by assuming that each relevant parameter has a stochastic character, which can be described with the expectancy value, a standard deviation and a statistical distribution. Uncertainties concerning the calculation models can be implemented too. As described before, the liquefaction calculation model yields the eigenvalue λ. This λ can be conceived as a function of the stochastic variables so that λ may be used as the reliability function in a probabilistic analysis. The probability analysis yields two results:

- the probability of the occurrence of a flow slide
- the contribution to the uncertainty of each of the parameters to the total failure probability.

The latter result enables the designer to decide whether additional investigations may help to increase the reliability of the assessment of potential flow slides. In this way, the design cycle of modelling and determining input parameters can be optimized.

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