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SYNOPSIS All available methods to obtain insight into the flow slide susceptibility have been applied on one location. This demonstrates, that the level of available knowledge is of influence on the quality of the advice. An overview of the methods and the results is given. The results are discussed. The conclusion is, that advanced study improves the understanding of uncertainties, and therefore gives a better assessment of risks. In this case, insight lead to the advice that no expensive measures were necessary, at least for part of the location.

INTRODUCTION

A flow slide is an instability in which a mass of liquefied sand, originally standing under a fairly gentle slope, for instance 1 : 3, flows out into a very gentle slope, for instance 1 : 20 (see fig. 1). Flow slides have occurred frequently in the Netherlands (over one thousand in 200 years) in the province of Zeeland (Koppejan et al [1948]). Also, in artificially made islands (for instance Nerlerk in the Beaufort sea (Sladen et al [1985])) or during dredging activity flow slides may occur. Another example are the frequent flow slides in the Mississippi River Mouth.
Since 1985 fundamental research has been performed. By now, this has resulted in advanced methods to predict the flow slide probability. For one location all available methods were applied, and even extended. This provided the possibility to compare all available methods. Also, detailed insight into the flow slide probability of this particular location was obtained.

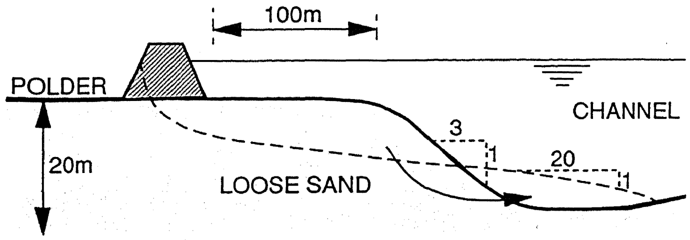

Figure 1 Geometry before and after flow slide

TRADITIONAL ADVICE METHODS

About 20 years ago, when no fundamental understanding about the phenomenon of flow slides was available, the only logical thing to do, was to try to analyse the records of flow slides that had already taken place in the past. Over two hundred flow slides were documented in sufficient detail to allow some basic analysis. From this empiric method, it was shown that flow slides mostly occurred when:

1. the slope was steeper than 1:3 to 1:5
2. the slope height exceeded 5 metres
3. the sand was loosely packed

This resulted in a prediction method, that simply stated that any situation in which all three conditions were satisfied were susceptible to flow slides. In that case measures, such as slope protection, had to be taken. Another observation, particularly important in this case, was the fact that 99 percent of all flow slides occurred in young holocene marine deposits.

THE LOCATION

At a location near the Zeeland Bridge in the Eastern Scheldt estuarium at least two of the conditions of the traditional advice method are satisfied: the slope angles varied from 1 : 2 to 1 : 5, and the average slope height was 20 metres. The question as to the density of the sand was answered by looking at the results of cone penetration tests. These indicated that at depths between 12 and 20 metres below sea level loose sand may be present. The soil at the site is an old marine holocene deposit. Traditional advice would result in the advice to take measures, but the fact that the sand was an old marine deposit, and not a young marine deposit, induced further study.

CRITICAL DENSITY

The first step towards a more fundamental approach is the concept of critical density. It can be demonstrated that, if a shear stress is applied to loose sand, the soil decreases in volume, whereas densely packed sand increases in volume. The reason for this difference is shown in figure 2. This phenomenon is called the dilatant behaviour of sand. The transition between loose sand and dense sand may be called "critical density" (Lindenberg & de Koning [1981]). This critical density is different in drained tests compared to undrained tests. The dry critical density allows no volume decrease at all, whereas the wet critical density depends on the question whether the sample will fail during the test. The dry critical density is conservative, the wet critical density might be too optimistic. Concluding, it can be stated that only sands with densities between wet and dry critical density are susceptible to liquefaction.
To make an evaluation based on critical density possible, three steps have to be taken:

1. In-situ density has to be measured, for instance with electrical density tests
2. Borings have to be made to obtain samples for laboratory research
3. Wet and dry density tests have to be performed.

All three steps were performed. This resulted in figures like figure 3. In-situ density in general is found between the wet and dry critical density.
Again, no definite answer is given: either measures have to be taken or more information has to be obtained.

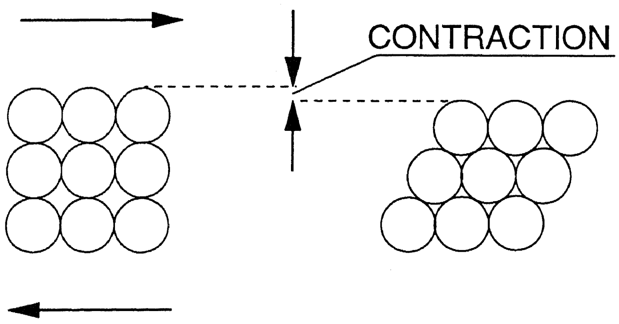

Figure 2 Loose sand and dense sand

STABILITY CRITERION BASED ON TRIAXIAL TESTS

One of the most important features of the critical density concept is, that it only deals with density as a criterion. This is however, as we have seen, only one of three criteria; slope height and slope angle are also of importance. It is, however, relatively easy to show the influence of slope height and slope angle on the flow slide susceptibility with the help of undrained behaviour of sand.
This behaviour can derived from the results of drained triaxial tests (Lindenberg & de Koning [1981]) as shown in figure 4. These tests yield the volume changes due to dilation as a function of the relative shear stress, s, and the volume changes due to decompression as a function of the mean effective stress, p'. These two volume changes have to counteract each other under undrained conditions, as no volume change can occur. From this condition the undrained stress path can be derived.

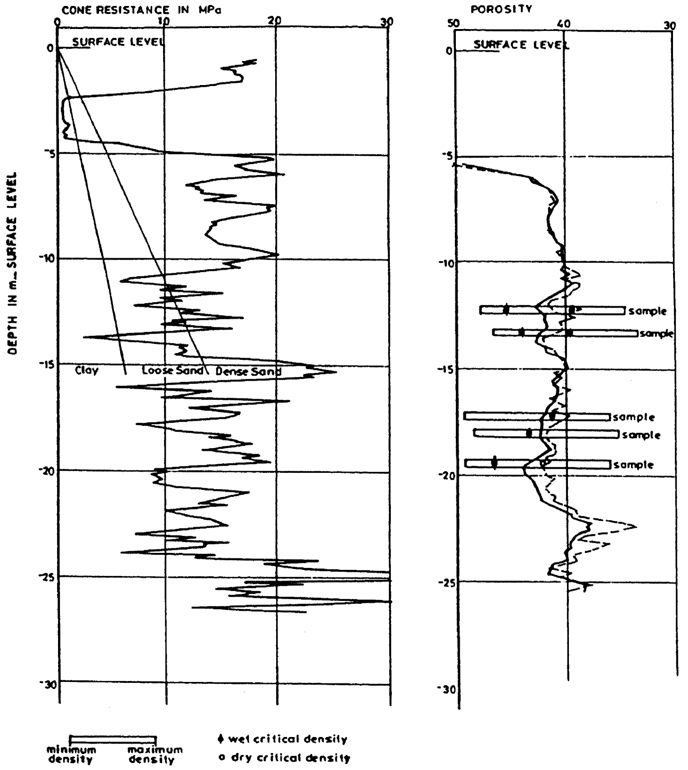

Figure 3 Results of field and laboratory research

With loose sand, this stress path looks like indicated in figure 4. Characteristic is the point B. If the stress state of any undrained soil element corresponds to that of point B, then a small increase in deviatoric stress must lead to a large decrease in effective stress, in other words: large pore water pressures. This may cause liquefaction.

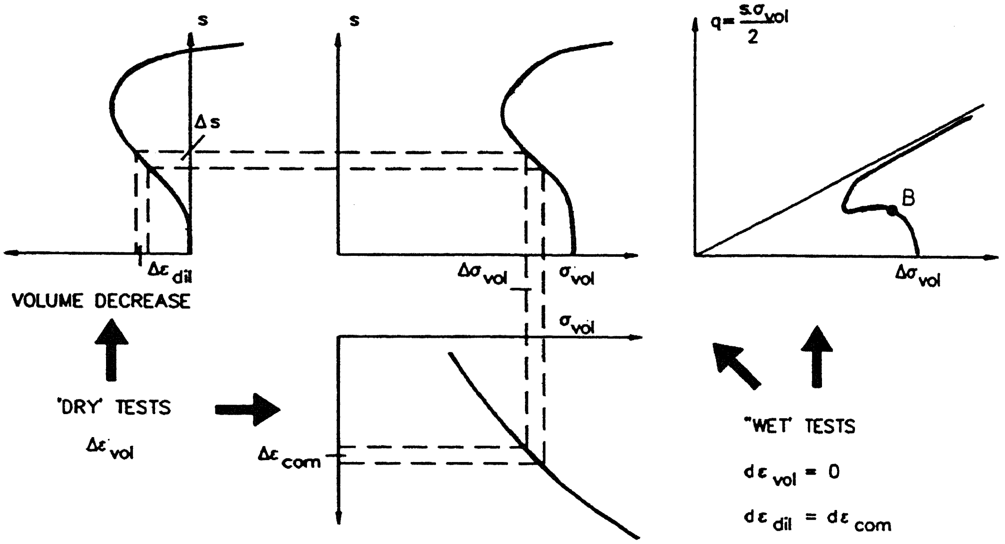

Figure 4 The relation between drained and undrained triaxial tests

As shown in figures 5 and 6 this proces coincides with large shear strains. In the flow slide model the stability criterion, formulated as:

$$d\gamma = \frac{1}{\lambda} \cdot d\tau_{xy} \qquad (1)$$

demands that for stability λ must be larger than zero. The term dγ denotes the change in shear strain and $d\tau_{xy}$ the change in shear stress. λ is called the eigenvalue and is in fact the eigenvalue of a matrix system comprising the entire system of stress-strain relations.
If the shear stress is written as:

$$\tau_{xy} = \gamma \cdot d \cdot \sin\alpha \qquad (2)$$

it is obvious that a decrease in shear stress leads to a decrease in slope angle. This is considered to be unstable behaviour.
In the flow slide model the parameters needed to calculate the value of λ are derived from drained tests. However, as shown, it will perform under undrained conditions also.
In figure 5 the influence of slope angle is explained. If the slope becomes steeper, the effect on the stress will be, that for the same effective stress, a larger shear stress will be found. This means, that the top of the curve may be reached. From this point on, instability may occur.
In figure 6 the influence of slope height is shown. If the slope becomes higher, the same shear stress will occur at a higher effective stress level. This means, that the top of the curve will become lower, and therefore the risk, that the top will be reached is larger.

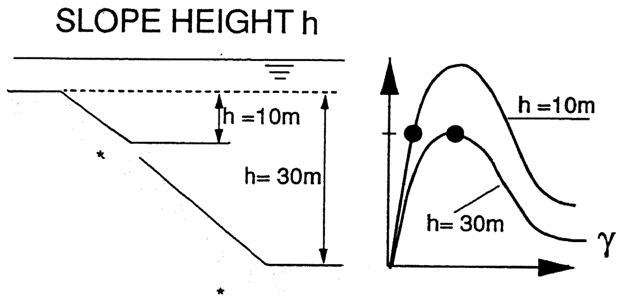

Figure 5 Influence of slope angle

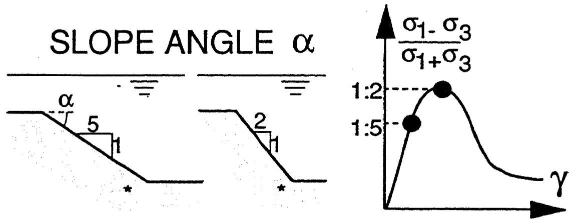

Figure 6 Influence of slope height

EXAMPLE OF CALCULATION

Shown in figure 7 is the result of one calculation. The lines mark the area in which instability has occurred at a given slope angle. The steeper the slope, the larger the area.
The model first determines the stresses as a function of slope height and slope angle. Next, for each point in the geometry the eigenvalue is calculated. This is done for a number of slope angles. In this way a figure like figure 7 is obtained.

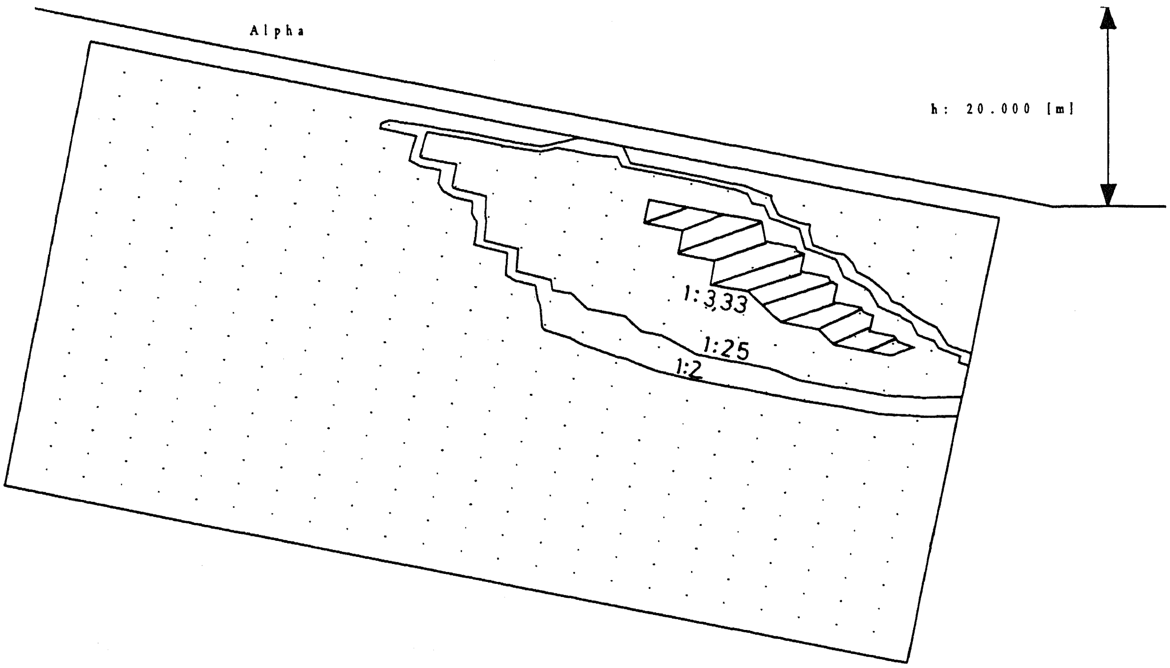

Figure 7 Result of one calculation

STATISTICAL ANALYSIS

For the location near the Zeeland Bridge, several samples of sand were tested in triaxial tests at different densities. In this way the results of a number of tests were available for calculation with the flow slide model. A connection between density and slope angle at which instability occurred according to the model was derived. This is shown in figure 8. The in-situ densities, as measured by means of electrical density probes, and slope angles are also given in this figure. A clear tendency is found, that if the density increases, the critical slope angle is steeper.
Assuming a statistical distribution, reliability intervals can be derived. If an appropriate level of safety could be chosen, a final answer to the question, whether the location is safe or not, can be given.
From figure 8, it is read, that for slopes 1 : 2 and 1 : 3, flow slide probability of the location is very high. However, in practice the situation is less unfavourable. There is a considerable spread in the outcome of the calculations. Uncertainties are introduced by inaccuracy of in-situ measurements, laboratory tests and possible deviations in parameters for the calculation model. If more would be known about these uncertainties, the reliability intervals can be drawn closer to the mean outcome of the calculations. To gain more insight in this problem one step further was made.

PROBABILISTIC APPROACH

It is also possible to make a probabilistic description of the problem. As the stability criterion is formulated as:

$$\lambda > 0 \qquad (3)$$

this can be used as a reliability function. The probabilistic approach can be described in 3 steps:

- determine the statistical distribution, the expectation value and standard deviation of each parameter
- define interdependencies between parameters
- calculate the chance that $\lambda < 0$

Some typical results of the probabilistic study are shown in figure 9. The influence of slope height and slope angle on the flow slide probability are clearly demonstrated. Again, as in the more simple statistical analysis, flow slide probability for the steeper slopes is very high. This is to be expected, as the introduced uncertainties are much the same.
The probabilistic method has the advantage over simple statistical analysis, that the contribution to the uncertainty in the answer

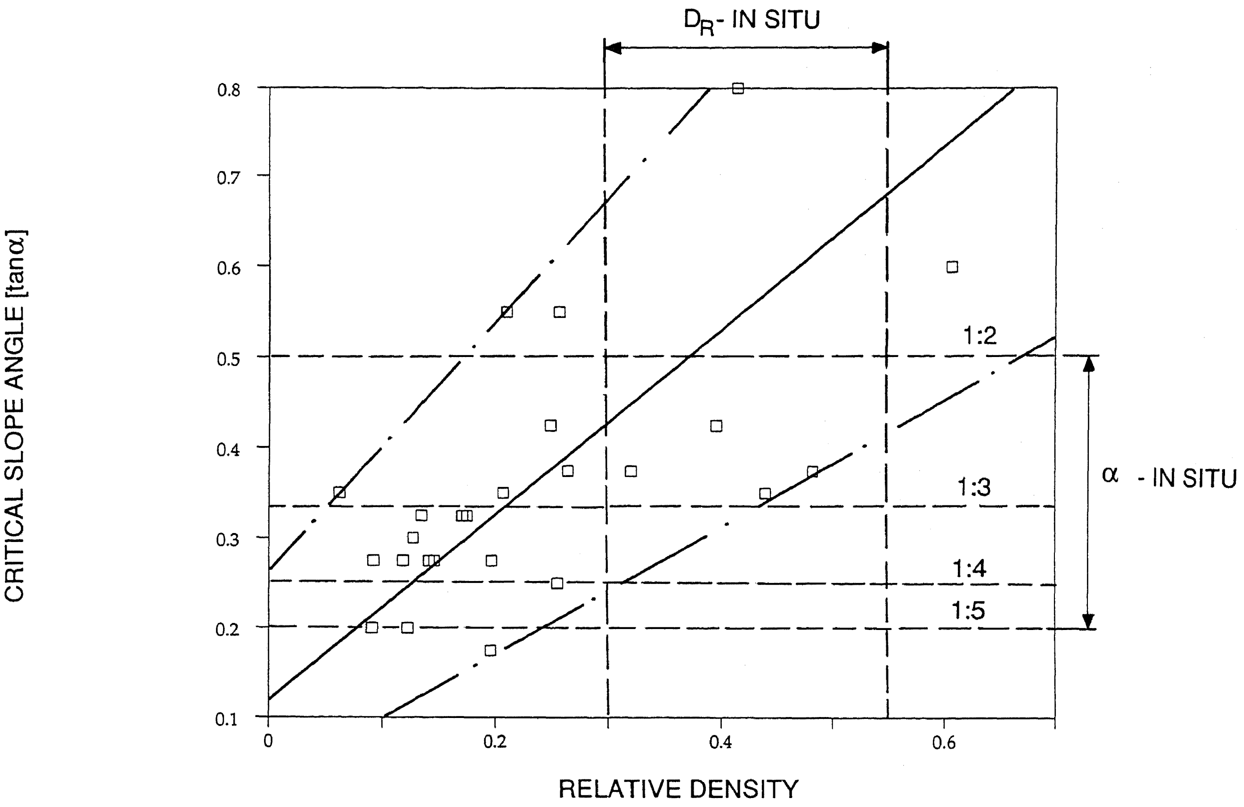

Figure 8 Monte-Carlo approach

can be obtained for each parameter separately. This identifies the most important uncertainties.

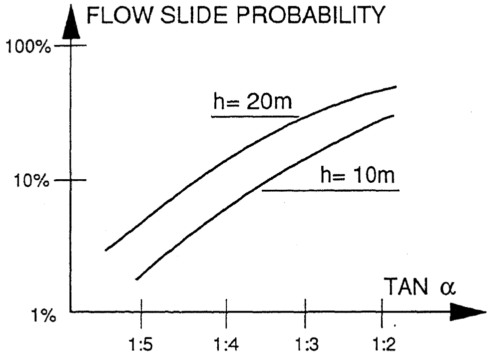

Figure 9 Result of probabilistic study

DISCUSSION

Choosing an appropriate level of uncertainty in geotechnics is often a difficult task. Large deviations in parameters are possible, for instance between two cone penetration tests at 50 metres distance. In this case, the question has to be answered, whether, if the return period of flooding due to failure of the dike would be for instance 1000 years, a chance of 1 percent of a flow slide occurring would be acceptable ? If not, it is very difficult to prove the chance is less, as there are many parameters, each with a considerable degree of uncertainty.

Chances as calculated seem very high. The model, however, probably is very conservative: one point in the geometry that shows instability is taken to be sufficient for liquefaction of the entire slope. In practice, a larger part will have to be liquefied before for instance a small slip circle failure and subsequent flow slide can occur. Also the favourable influence of drainage is ignored in the model. At the moment, further study to improve this conservative instability criterion is being performed. In the mean time, it is safe to say that the real chance of a flow slide occurring will be much lower than the calculated one.

Furthermore, the current situation has existed more or less unchanged during a period of time. Both these observations suggest no immanent danger is to be expected.

The emperic fact that old marine deposits are less susceptible to flow slides than young marine deposits, is not supported by any evidence found in these studies. Possibly stresses are different for both types of sand as a result of different stress history.

CONCLUSION/PERFORMANCE

Coming from traditional advice methods, through more advanced concepts, and ending at probabilistic studies more and more detailed knowledge is gained. This serves as a tool to make a more sophisticated estimate of the chance of a flow slide occurring. It still remains only an estimate of the chance, as even with the most advanced tools, no final answer can be given. In the case of the location near the Zeeland Bridge, traditional advice methods would have lead to expensive measures, such as protection of the foreshore. With current knowledge, the chance of a flow slide occurring is considered very small for the parts of the location with gentle slopes (1 : 4 or 1 : 5) or low slope heights (less than 10 m). No measures are needed, unless for instance scour would change the geometry. If the slope angle is steeper, and the slope height becomes larger, the flow slide probability is considered to be small, but not negligible. At the moment, the governing authorities have not decided yet on the question whether measures are needed for these parts. So far, no measures have been taken, and no change in slope angle has been observed for the last couple of years. This confirms the statement made in this paper about flow slide probabilities, that apparently are much lower than calculated with the model. However, the increased knowledge, gained by these advanced studies, has certainly helped to find a more economic solution to the problems of this particular location.

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