Chapter 19
A Semi-empirical Method to Assess Flow-Slide Probability

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Abstract Flow-slides in submerged slopes in non-lithified sand and silt-sized sediments form a major threat for flood defences along (estuary) coastlines and riverbanks in the Netherlands. Flow slide is a complex failure mechanism including both soil mechanical and hydraulic features. Two important sub-mechanisms are static liquefaction and breaching. Both result in a flowing sand-water mixture, that eventually re-sediments under a gentle slope. Therefore, when analyzing historical flow slides it is often not clear to what extent static soil liquefaction and/or breaching played a role.

This paper presents a practical, semi-empirical method for assessing dike failure probability due to flow-sliding. It is based on statistical information about documented historical flow slides, in which the results of complex theoretical models, describing physics of static liquefaction or breach-flow, are incorporated.

Keywords Flow slides • Dike failure • Risk analysis

19.1 Introduction

Flow slides in submerged slopes in non-lithified sandy or silty sediments form a major threat for flood defences along (estuary) coastlines and riverbanks in the Netherlands. Such flow slides may result in severe damage to dikes and structures. Measures to prevent, mitigate, or repair the damage caused by flow slides are costly. Due to the complexity of flow slides, methods enabling an accurate quantitative risk assessment are under-developed, especially compared to methods currently available for other failure mechanisms (e.g. backward erosion below the dike or macro-instability of the dike).

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In the past, dike failure probability due to flow-sliding was predicted using either simple but conservative empirical rules based on documented historical flow slides, in which no distinction between sub-mechanisms such as static liquefaction or breach-flow was made, or rather complex theoretical models describing the physics of these sub-mechanisms. This paper presents how both approaches can be combined into a practical, semi-empirical method for assessing dike-failure probability due to flow-sliding, accounting for uncertainties of the main influence factors.

19.2 Failure Mechanisms

Flow slide includes both soil-mechanical and hydraulic features. Two important types are static soil liquefaction and breaching. Both result in a flowing sand-water mixture, exhibiting the same post-event failure scarp morphology, characterized by a very gentle slope. Therefore in the analysis of historical flow slides it is often not clear to what extent each of the two phenomena was responsible.

19.2.1 Static Liquefaction

Static soil liquefaction entails the sudden loss of strength of loosely packed saturated sand or silt, resulting in a sudden collapse of the sand body. Contrary to "ordinary" slope failure, in which the instable soil mass slides along a clear rupture surface while staying more or less intact, in a liquefaction flow slide the instable mass of sand (or silt) flows laminar like a viscous fluid.

Generally, for static liquefaction in an under-water slope the following conditions are required (1) the presence of a sufficiently large zone of loosely packed, non-lithified, and water-saturated sand or silt; (2) the stress state of the loosely packed sand elements should be close to the so-called metastability point (i.e. the intermediate maximum in the stress path). For this, both mean stress and shear stress should be sufficiently large, which is only the case in a sufficiently high and steep slope; and (3) the presence of a trigger, for example a (small) load change.

19.2.2 Breach Flow-Slide

Unlike liquefaction and "ordinary" shear slope failure, *breaching* only takes place at the sand surface: a local steep part of the slope, the so-called "breach", retrogresses upslope and generates a turbulent sand-water mixture flow over the sand surface downslope. The velocity and discharge of this mixture will grow by erosion of the sand surface and entrainment of ambient water if (a) the initial perturbation generates a sufficiently high flow velocity carrying enough sand, and (b) if the local slope is steep enough. Since the retrogression velocity of the initial breach is relatively small a breaching flow slide generally takes much more time (several hours) than a liquefaction flow slide (several minutes).

Generally, for a breach-flow slide in an under-water slope the following conditions are required: (1) the presence of a sufficiently large zone of fine sand or silt; (2) a sufficiently high and steep slope; and (3) the presence of a trigger, for example scour or a local slope instability yielding a small but very steep slope section (breach).

19.3 Physical-Based Models

19.3.1 Static Liquefaction

Static liquefaction is widely discussed in literature (e.g. Jefferies and Been 2006). Examples of publications on the assessment of liquefaction-induced slope failure are Olson and Stark (2003) and Stoutjesdijk et al. (1998). Application of physical-based models usually requires an extensive local site-investigation and a large number of laboratory tests to assess necessary soil parameters. Insufficient accuracy in such assessments requires conservative estimations, resulting in unrealistically high failure probabilities.

19.3.2 Breach Flow-Slide

Validated equations governing the 1-dimensional stationary 2-layer flow and erosion processes, comparable with turbidity currents in combination with breaching can be found in Mastbergen and Van den Berg (2003). They are incorporated in the computer code HMBreach. The code allows assessing the sensitivity of an underwater slope with given geometry and sand properties to breaching, by calculating the minimum size of the initial breach for it to trigger a self-accelerating breach-flow. However, the tool has been validated only for restricted cases and the results are very sensitive to the applied friction and erosion model. Nor is exactly clear how the process develops when an upslope retrogressing breach reaches a contractive sand layer. Most likely, a local liquefaction flow slide, similar to the ones observed during large-scale flume tests (de Groot et al. 2012), will be initiated, which may trigger a breach flow slide upslope and/or downslope of a failed slope section.

A more advanced fully 3-dimensional flow model including turbulence generation, density flow, and sand transport processes is being developed in the software Delft3D-Flow (Lesser et al. 2004). Recently, computations simulating a breach-flow slide in the Eastern Scheldt have been performed successfully. However, the results still have to be validated with HMBreach and (scarce) field measurements.

19.3.3 Applicability of Physical-Based Models

Application of the theoretical models describing (parts of) flow-sliding is costly and does not always result in a reliable prediction of the flow-slide probability. The prediction accuracy of a flow slide depends on the (statistical and systematic) uncertainty of the input parameters and imperfection of the theoretical models themselves. High-level expertise is required to estimate the flow-slide probability using theoretical models, even when knowledge is available on local soil properties, slope geometry, and possible triggers. Although the theoretical liquefaction and breach-flow models are capable to quantify the relative influences of geometry and soil parameters, the reliability of the estimated probability remains limited.

19.4 Empirical Method

19.4.1 Basic Information and Mean Flow-Slide Frequency

A purely empirical method is based on documented historical flow slides in Zeeland, in the southwest of the Netherlands, as described by Wilderom (1979) and summarised by Silvis and De Groot (1995). Zeeland is a group of islands separated by tidal estuary channels which are part of the Rhine-Meuse-Scheldt delta. This dynamic area is characterised by alternating sedimentation and erosion along the channels. The consequent continuous gradual change in geometry of the submerged slopes results from time to time in a flow slide. These are probably initiated by a trigger (such as a rapid drop of water level), shortly after gradual erosion and sedimentation have caused a critical combination of slope angle and slope height.

According to Wilderom, the total number of flow slides along estuary banks in Zeeland between 1800 and 1978 was approximately 710. From the total length of (merely unprotected) estuary banks of approximately 190 km, the frequency of flow slides was found to be 0.02/km/year. This frequency can be used as a first rough estimate of the flow-slide probability in a similarly dynamic area with similar slopes and similar soil conditions.

19.4.2 General Applicability to Other Regions in the Netherlands

To what extent can the experience in Zeeland be applied in other parts of the Netherlands? The dynamic character of the shoals and channels in Zeeland may be similar to that of other tidal estuaries, but it is less in rivers and even less so in lakes. Application of the probability of occurrence found in Zeeland would result in overestimation of flow-slide probability. The similarity in slope geometry needs to be compared from case to case, as will be discussed below. The general similarity in soil conditions follows from a comparison between the geology of other parts in the Netherlands with that of Zeeland, as presented in the following sections.

The geological past of Zeeland is characterised by rapidly shifting coastlines. Generally the upper 30 m of soil consists of Holocene deposits. Most of these consist of (medium) fine sand, which, in general, is loosely packed due to high deposition rates. The variation in tidal currents often resulted in thin clay layers in between the thicker sand layers.

The depositional environments in which sand accumulations formed in other parts of the Netherlands have been rivers, tidal waters, open coast shorelines, coastal sand flats, and periglacial sand deserts (see for example Schokker et al. 2007). Loose packing of sand is present in all these deposits. The combination with clay and peat layers (determines dissipation of excessive pore pressures) makes these deposits sensitive to liquefaction (Hicks and Onisiphorou 2005).

Thus, soil conditions relevant for the occurrence of flow slides in other parts of the Netherlands can be considered to be generally similar. Nevertheless, *local* soil conditions may significantly deviate from the mean conditions in Zeeland and need to be considered for each case separately.

19.4.3 Influence of Local Soil Characteristics and Slope Geometry

Application of the mean probability on a flow slide may be justified for a specific stretch of slope which has the characteristics of a "mean slope". For cases with lower or higher packing or other slope characteristics the probability will be different. Below we discuss how the expected probability can be adjusted to local characteristics.

A first source of information for such adjustment can be found in Wilderoms documentation of each flow slide. It includes parameters of the under-water slope geometry prior to the flow slide and general information about the local soil conditions and triggers for various bank stretches along the shores of Zeeland. Part of this information is illustrated in Figs. 19.1 and 19.2.

Figure 19.1 shows the influence of the type of deposits. Generally, the flow-slide frequency decreases with increasing age of the deposits. There is, however, a large variability among the different bank stretches. Some are much more sensitive than others; others even show an opposite tendency with respect to the influence of geology. The variability shows the large influence of other factors than the soil type in geological terms.

Large variability can also be observed if only slope angle is considered (Fig. 19.2).

Although these data contain a wealth of information, until now it has only been used to relate average site properties to an average flow-slide probability (i.e. a mean slope height (H_R) of 24 m, a mean slope angle of 1:5, an estimated mean relative

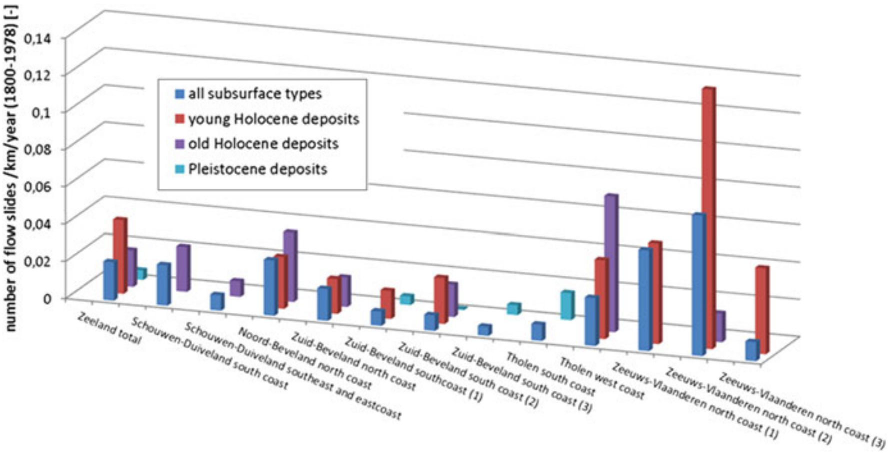

Fig. 19.1 Flow-slide frequency for all Zeeland banks documented by Wilderom (1979) and its 12 bank stretches as a function of geology

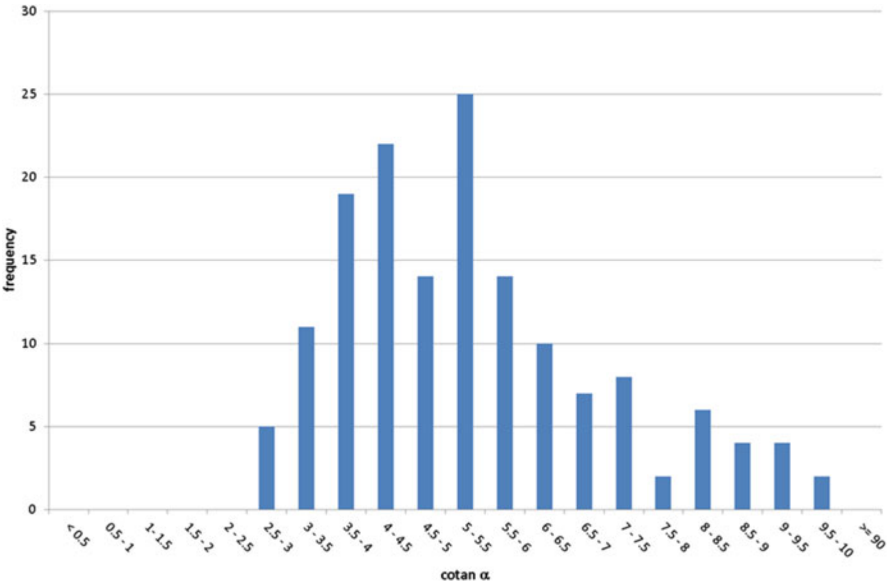

Fig. 19.2 Histogram with cotangent of average slope angle (α) of flow slides in Zeeland documented by Wilderom (1979)

density of 30 % (corresponding with $\psi = -0.05$, see Van Duinen et al. 2013) and an estimated mean median grain size of $2 \cdot 10^{-4}$ m). A multiple regression analysis would have been a good option, had the observations on the different site characteristics and flow-slide occurrences been paired. Unfortunately they were not.

19.5 Semi-empirical Method

Due to the limited possibilities for quantifying the influence of site characteristics on flow-slide probability using empiric data only, a semi-empirical method has been developed. The method takes the flow-slide probability for the mean slope as a starting point, and quantifies the influence of local deviations using the theoretical models described earlier.

Since other information is lacking, it may be assumed that half of all flow slides registered by Wilderom (1979) have been pure liquefaction flow slides while the other half concerned pure breach flow-slides (in reality many flow slides were presumably a combination of both mechanisms).

Therefore the flow-slide probability can be written as:

$$P\,(ZV) = 0.5 \cdot P\left(ZV_{liquefaction}\right) + 0.5 \cdot P\left(ZV_{breachflow}\right) \qquad (19.1)$$

It is assumed that the occurrence of liquefaction is mainly influenced by (1) the stress state, which can be expressed by a so-called fictitious slope height (in which the influence of the above-water part of the slope is included (H_R)) and an average under-water slope angle (cotanα_R); and (2) the packing of the potentially liquefiable layer (expressed by relative density, I_D, or state parameter, ψ). The thickness of this layer is assumed to be 5 m, since this is the minimal thickness required for slope instability due to liquefaction.

Besides slope height and angle the occurrence of an unstable breach flow is assumed to be mainly influenced by medium grain size.

The probabilities on a liquefaction flow-slide and breach flow-slide can thus be expressed by:

$$P\left(ZV_{liquefaction}\right) = f1\,(H_R) \cdot f2\,(cotan\alpha_R) \cdot f3\,(density) \qquad (19.2)$$

and

$$P\left(ZV_{breachflow}\right) = f4\,(H_{RB}) \cdot f2\,(cotan\alpha_R) \cdot f5\,(D_{50}) \cdot f6\,(claylayers) \qquad (19.3)$$

which can, together with Eq. (19.1), be combined into:

$$P\,(ZV) = f2\,(cotan\alpha_R) \cdot \{0.5 \cdot f1\,(H_R) \cdot f3\,(density) + 0.5 \cdot f4\,(H_{RB}) \cdot f5\,(D_{50}) \cdot f6\,(claylayers)\} \cdot 0.02km^{-1} \cdot year^{-1} \qquad (19.4)$$

Note that for breach flow the definition of slope height may be different than for liquefaction. For that reason different symbols are used (H_R vs. H_{RB}).

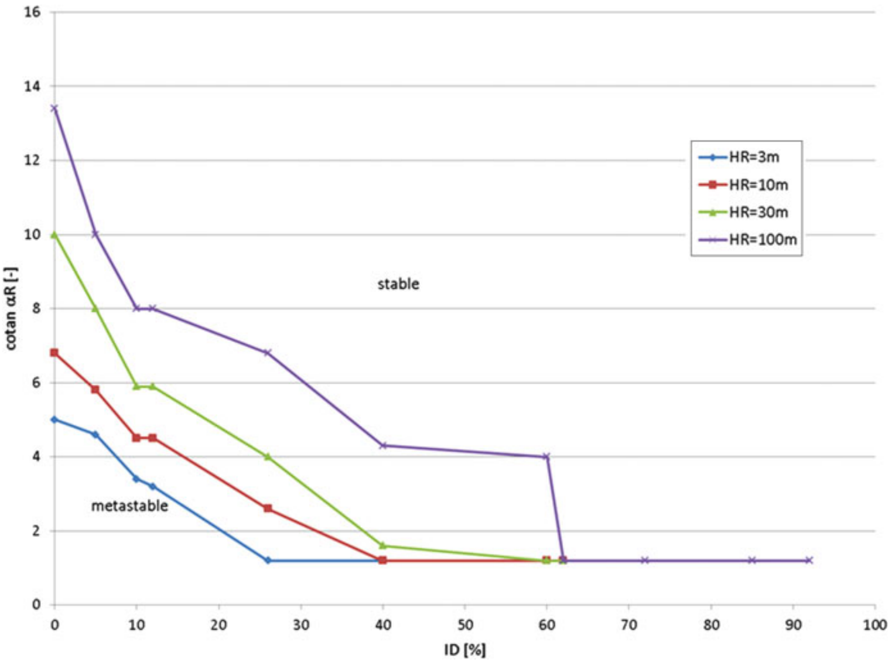

Fig. 19.3 Influence slope height (H_R), slope angle (cotα) and relative density (I_D) on the occurrence of metastability, as calculated with SLIQ2D (Modified from Stoutjesdijk et al. 1998)

19.5.1 Determination of P(ZV$_{liquefaction}$)

Figure 19.1 shows that the flow-slide frequency in "young Holocene deposits" is roughly twice as much as in "old Holocene deposits". Thus the frequency increases by a factor two if the relative density decreases by 10 %, or a corresponding increase of the state parameter by 0.05.

From sensitivity analyses with the liquefaction programme SLIQ2D (Stoutjesdijk et al. 1998) it appears that a decrease in relative density has roughly the same effect on the size of the metastable area as an increase of the slope height by a factor three (e.g. from 10 to 30 m) or an increase of slope angle by a factor 1.5 (e.g. from 1:6 to 1:4), see Fig. 19.3.

This leads to:

$$f1\,(H_R) = \left(\frac{\boldsymbol{H_R}}{\mathbf{24}}\right)^{\mathbf{2.1}} \tag{19.5}$$

$$f2\,(cotan\alpha_R) = \left(\frac{\mathbf{5}}{\boldsymbol{cotan\alpha_R}}\right)^{\mathbf{5.7}} \tag{19.6}$$

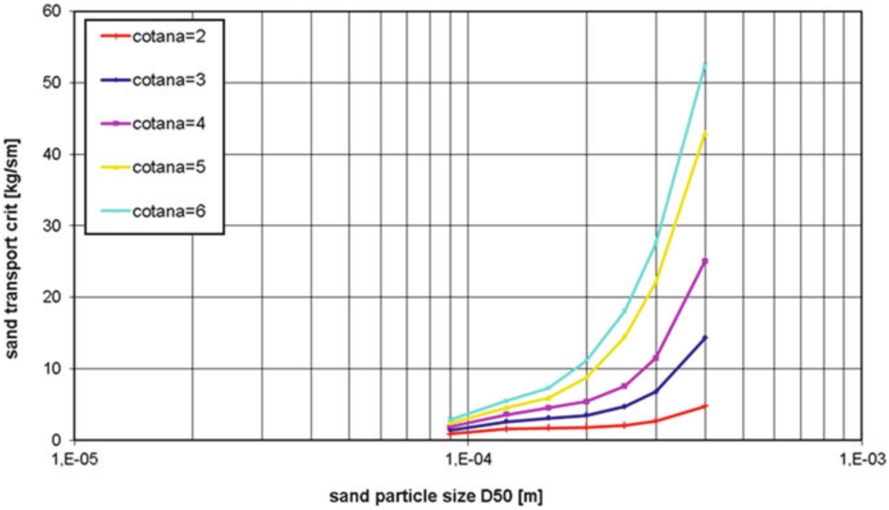

Fig. 19.4 Influence of grain size and slope angle on critical perturbation according to HMBreach

$$f3\,(density) = \left(\frac{1}{3}\right)^{\mathbf{10}\cdot(I_D-\mathbf{0.3})} \tag{19.7}$$

In the above equations the term describing the influence of relative density $\left(\frac{1}{3}\right)^{\mathbf{10}\cdot(I_D-\mathbf{0.3})}$ can be replaced by a term based on state parameter (ψ).

Reduction in slope angle from 1:5 to 1:11 yields a 100 times smaller probability. This agrees with the observations in Fig. 19.2.

Since it is unknown whether the flow slides registered by Wilderom are liquefaction or breaching flow-slides, the term $\left(\frac{5}{cotan\alpha_R}\right)^{5.7}$ applies for breach flow-slides as well.

19.5.2 Determination of P(ZV$_{breachflow}$)

Figure 19.4 presents the result of a series of HMBreach calculations for homogeneous sandy slopes. The critical value of the initial breach, i.e. the value that just causes a self-accelerating turbulent sand-water mixture flow and here expressed as sand transport sz, is presented on the vertical axis. The horizontal axis presents the mean grain size, whereas each curve is valid for a certain slope angle. The same value of the critical initial breach is assumed to correspond to the same probability on a breach flow. This makes clear that a decrease in grain size from $D_{50} = 2\cdot10^{-4}$ m to $1.25\cdot10^{-4}$ m yields the same value of the critical perturbation (i.e. sz = 5 kg/sm) if the slope angle is reduced from cotanα = 4 to cotanα = 6.

This means that f5 can be expressed as:

$f5\,(D_{50}) = \left(\frac{2\cdot10^{-4}}{\boldsymbol{D_{50}}}\right)^{\boldsymbol{E}}$ where $\frac{f5\left(1.25\cdot10^{-4}\right)}{f5\left(2\cdot10^{-4}\right)} = \frac{f2(6)}{f2(4)}$ or $\left(\frac{1.25\cdot10^{-4}}{2\cdot10^{-4}}\right)^{E} = \left(\frac{6}{4}\right)^{5.7}$, which yields E = 5.

In a similar way $f4\,(H_{RB}) = \left(\frac{\boldsymbol{H_{RB}}}{\mathbf{24}}\right)^{\boldsymbol{D}}$ with $D = 4$ is found.

Finally $f6$ is introduced because the presence of cohesive layers within the sand body increases the probability of a trigger. Undermining of these layers by the upslope moving breach may cause these layers to break down resulting in a sudden increase in the height of the vertical breach. This leads to a sudden increase in sand discharge and increase of erosion. Cohesive layers start to play a role if their (individual) thickness is larger than 0.5 m. If their thickness exceeds 5 m it can be assumed that the breach will stop.

In case a small number of relatively thin clay layers is present, as in the Holocene deposits in Zeeland, $f6\,(claylayers) = F = 1$ holds. Since the present version of HMBreach cannot account for cohesive layers, values for F for other situations have been estimated. F may vary between 1/3 (no clay layers) to 3 (many clay layers).

This results in:

$$\boldsymbol{P}\,(ZV) = \left(\frac{5}{cotan\alpha_R}\right)^{5.7} \left\{0.5 \cdot \left(\frac{H_R}{24}\right)^{2.1} \cdot \left(\frac{1}{3}\right)^{10\cdot(I_D-0.3)} + 0.5 \cdot \left(\frac{H_{RB}}{24}\right)^{4} \cdot \left(\frac{2\cdot10^{-4}}{D_{50}}\right)^{5} \cdot F_{cohesivelayers}\right\} \cdot 0.02\ \mathrm{km}^{-1} \cdot year^{-1} \quad (19.8)$$

19.6 Concluding Remarks

The presented semi-empirical method for calculating the probability of occurrence of flow slides has a solid base in the documentation of historical flow slides. The incorporation of the results of theoretical models describing the physics is promising, but needs further development. The theoretical models on breach flow-slide need further development and validation, including the interaction with static liquefaction. The respective factors in the semi-empirical equation need to be adapted accordingly. The role of the dynamic character of banks needs to be investigated such that the effects of gradual change of geometry and triggers can be incorporated. This will likely result in lower predicted probabilities for slopes in banks with a less dynamic character.

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