

Overview geotechnical model tests on dike safety at Deltares

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Abstract: Three on-going dike safety studies (on: macro stability, piping and flow slides) in the Netherlands make use of geotechnical physical models. A short outline of these projects is presented; the physical models chosen are described and discussed. The three studies use different physical models, depending on the research questions at the beginning of the model test series, the heterogeneity that is anticipated in the field, the scaling laws and the knowledge level. The paper describes why a certain model was chosen.

Keywords: Macro stability, piping, flow slides, physical model approach.

1 INTRODUCTION

Dike safety is of great importance in the Netherlands to protect the country against flooding by storm surges or high water levels in the rivers. Flood defences along (estuary) coastlines and riverbanks in the Netherlands are checked every six years to assure that the required safety levels are met. These checks are also used to identify 'knowledge gaps': situations where our understanding of the mechanisms involved is insufficient to come to an adequate judgment whether the safety level is sufficient to meet the required safety levels. These knowledge gaps drive research within the SBW programme (SBW is the Dutch abbreviation of Strength of and Loading on Flood defence structures) with the aim to increase our knowledge within six years to be able to perform the next check on that water defence with sufficient knowledge. Another reason for research is economical optimization: some design rules are believed to be too conservative. Research can then lead to sharper limits and less repair works.

In the context of this programme the geotechnical work performed by Deltares focuses on macro stability, piping and flow slides. Other papers at this conference (Van Beek et al 2012, De Groot et al 2012 and Zwanenburg 2012) describe the details of the tests performed. This paper concentrates on how a selection was made between different possible physical models depending on the research questions at the beginning of a model test series, the heterogeneity that is anticipated in the field, the scaling laws and the knowledge level of that particular mechanism at the start of the research. The choice of the physical model tool in research often budget driven, but it will be shown that, there are also technical reasons to choose specific tools.

2 MACRO STABILITY

2.1 Context

A 40 km long dike between Hoorn and Amsterdam, along lake Markermeer, is founded on organic clay and peat layers. These dikes did not pass the six-yearly safety check that is performed on dikes in the Netherlands. This safety check considers different failure mechanisms including large slip planes through

dike and subsoil. In the Dutch codes and handbooks this type of failure is referred to as Macro Stability. For the Hoorn – Amsterdam section limit equilibrium analyses showed in most cross-sections along the dike a factor of safety lower than 1 for these large sliding planes. This outcome was somewhat unexpected since the dike was constructed before the building of the closure dam, Afsluitdijk, in the North, when there was still tidal water at the Markermeerdijk. By that time the loading on the dike was higher than at the present design conditions. This led to the idea that the safety check is too conservative. Although it should be noted that the present design conditions involve a lake level raise for several weeks, while the storm surges from the past had a time scale of 24 to 48 hours.

The explanation of the difference between the calculation results and engineering judgement is found in the still not well understood behaviour of peat. Fibres present in the peat might make conventional laboratory tests unsuitable for parameter assessment, causing the high scatter found in test series on peat. Poor characterization of peat samples makes classification in different peat types impossible, thus further increasing the scatter.

2.2 Tests performed

It was therefore decided to perform field tests to test the field strength of this peat. Since it is not allowed to destabilize a water defence, two types of tests were foreseen:

- A series of 6 field trials, in which sliding plane through the peat is forced. These tests allow for a comparison between field strength and laboratory tests.
- A series of 14 triaxial tests on samples with a diameter of 0.4 m and a height of 0.8 m. .

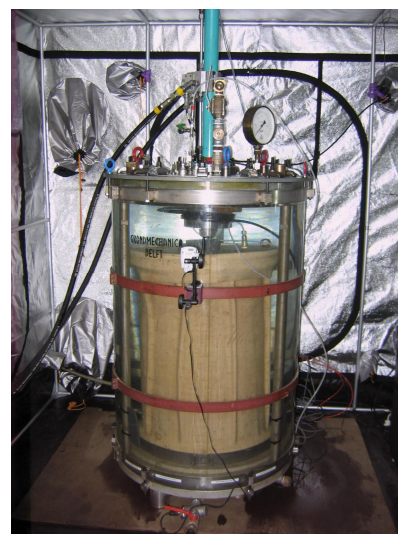


Figure 1. left: pre-loading for multistage loading tests, concrete slabs, in wintertime. right: large triaxial test.

A specific location along the dike section Hoorn – Amsterdam was found where the field trials were executed in the land directly behind the dike, see Figure 1. The test series is divided into single stage loading tests, in which the soil is tested in its original condition and multi stage loading tests in which the influence of a pre-loading on peat strength was tested. In the same field a large field survey is conducted including CPTU testing, ball penetrometer tests, conventional borings and large diameter sampling. This allows for studying heterogeneity of peat at different levels. The CPTU and ball penetrometer provides information at nearly mm scale, conventional laboratory testing at cm scale, large triaxial tests on dm scale and field trial on m level. Finally, a last step on km scale is required to apply the results to the entire dike section. Since the scale of the largest peat fibres is between 5 and 10 cm, it is expected that the large scale triaxial tests and the field trial will not be influenced by scale effects from the fibre length.

2.3 Selection of physical model

The failure mechanism macro stability for dikes is well understood and tested in centrifuge tests (Van et al. 2005). The influence of pore water pressures in the polder behind the dike on stability is known. A dike failure in 1984 at Streefkerk has led to research by which the phenomenon could be well described and validated: a number of centrifuge tests and a field test in Bergambacht (Van et al. 2005) were performed. The failure in Wilnis, in 2003 showed the influence of draught and again pore water pressures (Bezuijen et al. 2006).

The real problem in establishing the safety of a dike against macro instability is the heterogeneity and anisotropy of the subsoil and its influence on the stability. Therefore, the soil in the test should have the same layering and load history as the in-situ soil at the Markermeerdijk. Identical soil layering can be best achieved in a field test where the same soil can be used as in prototype. Since the research goals are directly related to the specific conditions along the Hoorn – Amsterdam dike section and the influence of scale of heterogeneity is an important issue, centrifuge tests were not conducted in this phase of the study. It should be noted that field tests have interpretation problems as well. The translation of the results from the test site to the peat underneath the dike and from there to the entire 40 km dike section involves large uncertainties.

The large triaxial test facility gives the option to study directly the scale influence. The test procedure of large triaxial tests are identical to the conventional triaxial tests. So, any significant difference between both are somehow linked to scale differences.

3 PIPING

3.1 Context

Piping (or backward erosion) is considered to be the main failure mechanism for the Dutch dikes (Floris study, 2005). Figure 2 shows the principle of piping. Sand boils are regularly seen along rivers during high water; see Figure 3, although the water level during these conditions is still significantly lower than during design conditions.

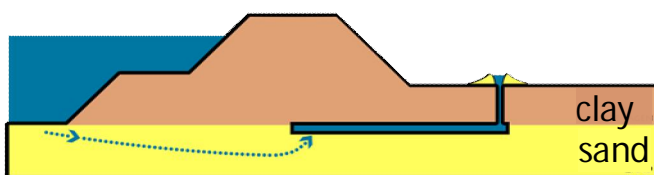


Figure 2. principle of piping or backward erosion.

Fig



Figure 3 : Sand boil during high water period of 2011 (Hurwenen, The Netherlands)

Piping is studied by Bligh (1918) and Lane (1935) and general rules were established. Theoretical work of Sellmeijer (1988) and experimental work (De Wit et al. 1981) led to more refined rules, including the influence of scale and the grain size. After a safety study indicated that this mechanism is a dominant failure mechanism for several dike rings in the Netherlands (Floris 2005), a research program was

initiated to investigate whether or not the model of Sellmeijer was conservative as well as to provide an experimental validation of the existing design rules. Hereto the influences of grain size, grain size distribution, density of the sand and roundness of the grains on the critical head were investigated. Furthermore, the theory developed is a 2-dimensional theory while the problem itself is 3-dimensional, see Figure 4. It was assumed that calibration of the 2-D model with 3-D tests was sufficient to ensure sufficient accuracy, but this was not proven (Weijers and Sellmeijer, 1993).

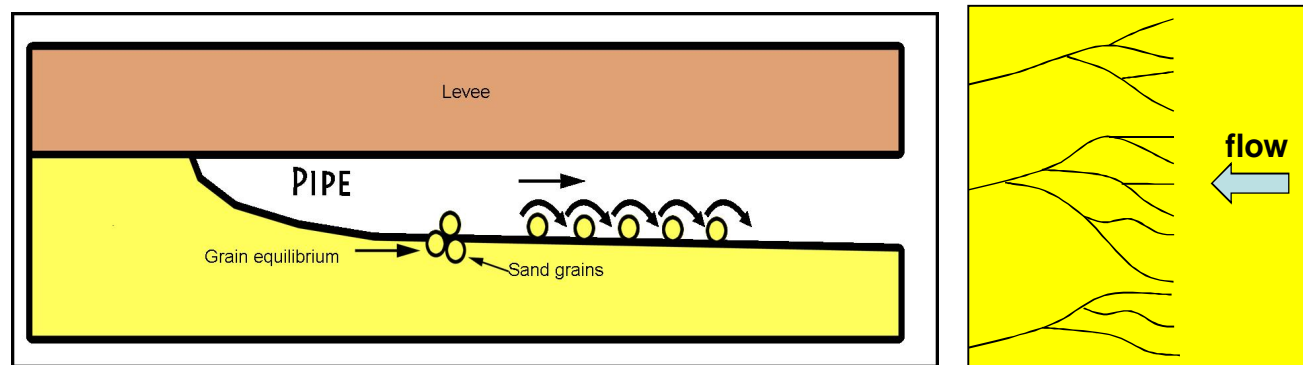


Figure 4. 2-D model (left) and realistic flow pattern (right).

The results of this research programme have led to an adaptation of the existing calculation models (Sellmeijer et al. 2011). The influence of the grain size appeared different from the theory and the relative density appeared to have a significant influence. Furthermore, it was realized that there are quite some geometries where piping may occur that were not covered in the existing design rules (for example flow to a single hole in the impermeable clay layer, as well as sand layers with different permeabilities). These findings led to an expansion of the research programme and it now includes experiments, analytical and numerical modelling and field observations. This paper focuses on the model tests performed.

3.2 Tests performed

3.2.1 Summary of tests

Quite different tests were performed. The tests range from element tests to physical model tests. The following tests were performed, or will be performed in 2012:

1. Small scale 2-dimensional element tests to check the mechanisms that cause piping.
2. Small scale tests to investigate the influence of various sand characteristics on the process and the critical head.
3. Small scale tests that allow for observation of the piping channel on two sides to investigate the mechanism.
4. Small scale tests in a geotechnical centrifuge at 30g.
5. Model tests on a dike built on sand in a geotechnical centrifuge at 80g.
6. Medium scale tests to test the influence of scale
7. Field tests by constructing a dike on sand

Before going into the description of some of these tests, it is necessary to deal with the scaling rules for piping tests, also described in Bezuijen and Steedman (2010).

3.2.2 Scaling rules

A particular feature of piping erosion that affects its potential to be modelled in a 1-g or n-g model test is the rather unusual scaling effects for this mechanism. The groundwater flow pattern will have the same shape in model and prototype but with smaller dimensions in the model, see Figure 5. Consequently the area with critical gradients will be smaller in the model. However, the grain size is the same in model and

prototype and thus less grains are subjected to high gradients close to C in Figure 5. Assuming that a number of grains must be loaded with a certain gradient to start a pipe it was shown by Bezuijen and Steedman (2010) that the critical gradient is a function of the length scale of the model:

$$\frac{H_c}{L} \propto \frac{1}{\sqrt{L}} \quad (1)$$

Where $L=2B$ in Figure 5, the length of the impervious upper layer and H_c is the hydraulic head over the structure.

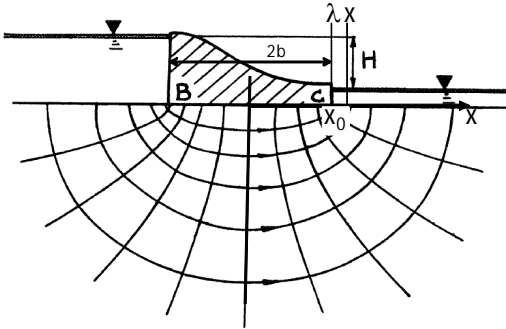


Figure 5. Sketch for groundwater flow calculation.

However, when a pipe exists between the impervious layer and the sand the situation becomes different. In that case the pipe can only become longer when not only sand grains are loosened from the sand bed, but also these grains has to be transported through the pipe. Sellmeijer (1988) has investigated the latter situation (the ‘propagation’ mechanism) theoretically and found again an influence of the critical gradient to transport grains through the pipe with the length scale but now the gradient across the levee i_a is not proportional to the inverse of the square root of the length L but to the cubic root:

$$\frac{H_c}{L} \propto \frac{1}{\sqrt[3]{L}} \quad (2)$$

3.3 Selection of the physical model

A consequence from the scaling aspects for the piping process is that not only the critical head, but also the dominant mechanism depends on the scale. Due to different scale effects for initiation and progression, in small scale tests the start (or initiation) of a piping channel will be dominant compared to progression. At a larger scale the required head for progression of the pipe will exceed the head for initiation, and may become dominant (Bonelli et al. in press, 2012). Due to the scale effects, experiments at small scale tests should be designed carefully, and can only be used to develop the theory of the piping mechanism, rather than as scale tests of a prototype situation. Tests on larger scale are necessary for validation of scale effects. For this reason tests were performed at different scales.

Small scale tests can be used to study a variety of situations

The two-dimensional small scale tests were not performed to get quantitative information on the piping phenomenon, but to see how the mechanism works. In these tests that were performed by Van der Zee (2011) the sand layer was only one cm wide. This was a suitable scale to study the mechanism that creates a pipe. It was shown, see Figure 6, that the piping process does not start with the creation of a pipe, but that there is a continuous movement of grains just below the impermeable upper boundary. However, due to the small dimensions, the pipe occurs at a very high critical gradient (H_c/L around 0.5). The main result of such small scale tests is, that it is now known what mechanisms has to be investigated

at larger scale, but the larger scale tests will be necessary to investigate whether the same mechanisms are available at a larger scale when the critical gradient is much lower (less than 0.05).

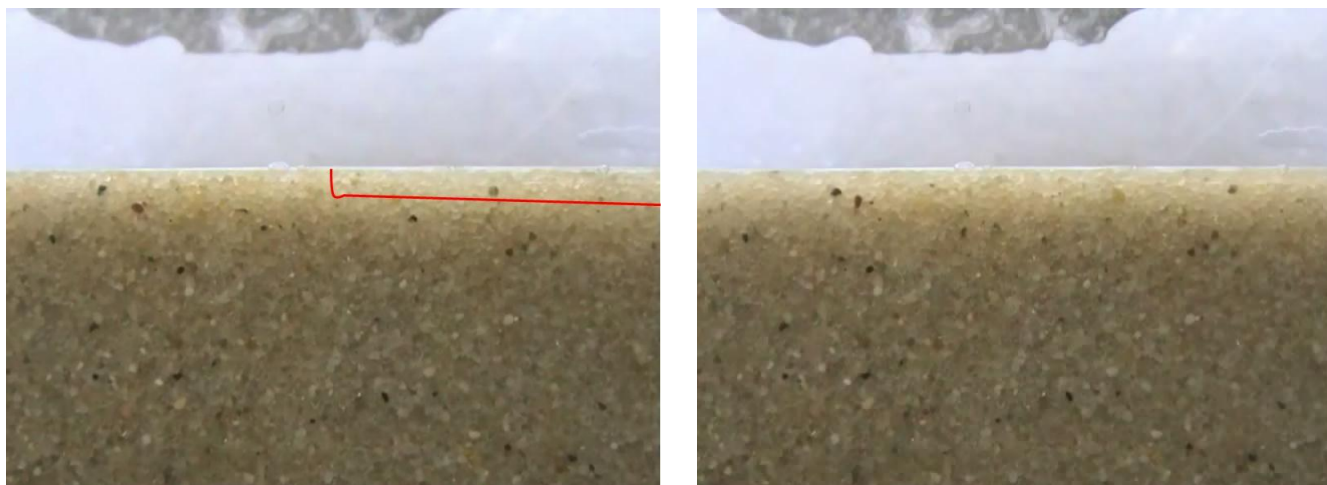


Figure 6. Results of 2-D small scale tests. The sand is confined to all sides by Perspex. The left picture is taken when the sand grains in right and above the red line started to move. The right is taken when the whole upper layer moved. It should be noted that although the sand grains move there is still no pipe.

Centrifuge tests

The tests performed in a centrifuge gave comparable results as the 1-g small scale model test: piping occurred at much larger hydraulic gradients than in tests performed on a larger scale, which can be explained by mechanisms described in Section 3.2.2. For the initiation mechanism the ratio between the dimensions of the dam and the dimension of the grain is the same in a 1-g small scale model and in a centrifuge model of the same dimensions. Also, for the propagation mechanism, it holds that the flow in a centrifuge model will be N-times faster than the flow in 1-g model. In this case the weight of the grains will also be N-times more, resulting in a comparable gradient at which the grains will be transported through the pipe. Only if there is a bit more turbulence due to the higher flow velocities, the centrifuge model will result in lower critical gradients than the 1-g model. This was also found in the tests, see Figure 7. The gradients found were much higher than found in the field. Due to this the stability of a normal dike under piping could not be investigated in the centrifuge. A special model with a steep slope was necessary to create failure due to piping, see Figure 8. More information on the centrifuge tests can be found in (Van Beek, 2010)

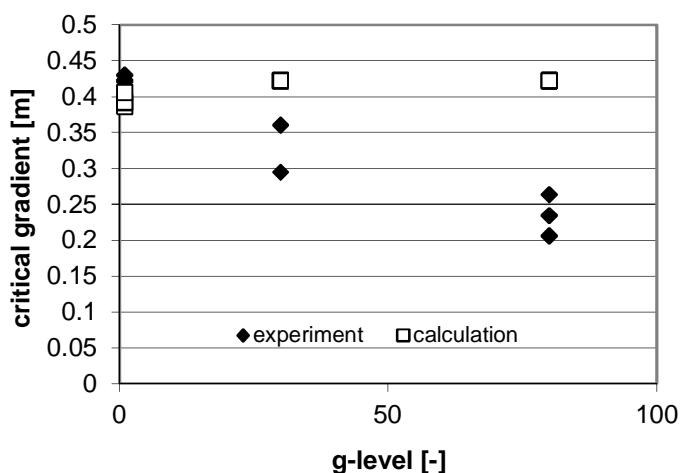


Figure 7. Critical gradient as a function of the g-level in centrifuge tests (Beek et al., 2010).



Figure 8. Dike model used for piping tests. The vertical wall was necessary to create sufficient high gradients.

Medium scale tests and field tests

Medium scale tests and field tests, see Figure 9, were performed to check the failure mechanism and the scaling rules. Both types of test showed that the critical head was significantly lower than in the small scale tests, as was expected based on the scaling laws. A result that was new and only could be achieved in the field tests and not in the smaller scale tests was the mechanism that occurred after the pipe has reached the upper basin. It was anticipated that when an erosion pipe by backward erosion has reached the upper basin the failure of the dike was only minutes away. In reality this appeared more complicated, when the pipe reached the upper basin, the erosion in the upstream part through the pipe increases considerably. This increased amount eroded material cannot flow through the rest of the pipe. As a consequence the pipe is temporarily blocked and the erosion decreases, until there is again an open channel between the upper and lower basin. In the field experiments this process could take about 48 hours. This phenomenon could only be observed in the field measurements since only there a real dike was constructed and also parts of the settling dike can temporarily stop the erosion.



Figure 9: Failed dike in full-scale field experiments. The dike is 3 m high and 15 m wide. Water level was increased until 2.5 m.

4 FLOW SLIDES

4.1 Context

Flow slides regularly occur in the Dutch estuaries. They can damage or even lead to failure of dikes. An example of a near failure is shown in Figure 10. In the 70-ties the possible occurrence of flow slides resulting in dike failure was one of the reasons to develop the Eastern Scheldt Storm Surge Barrier, because strengthening the dikes along the Eastern Scheldt did not guarantee a sufficient safety level. Flow slides were studied extensively in the 70s and 80s of the last century (De Groot et al 2012). By that time it was thought that the liquefaction of loosely packed sand was the main cause of flow slides. Based on a report of flow slides at the Mississippi River in the USA (Torrey, 1995) and observations of slowly progressing failure of a sandy slope in the Waddenzee (Van den Berg et al., 2002), it was realized that also another failure mechanism can occur. In this case a local failure somewhere in the submerged slope (e.g. due to scour or a small slip failure) results in a sand-water mixture, that leads to further erosion of the slope and consequently to further instability, a mechanism that is also known in dredging as breaching of sand. The present day research is focused on what mechanism (either liquefaction or 'breaching') is most likely to occur and on the required trigger to start such a mechanism.



Figure 10. Near failure of a dike due to flow slide

4.2 Tests performed

During the 70s an extensive research programme was performed (De Groot et al. 2012). Since these tests are well documented and reported, it is possible to use the results of these tests to verify more recently developed theories with respect to the mechanisms. A total of 26 relatively large scale tests were performed in a flume of 3 m depth, with a sand height of 2 m of and a length of 60 m. Furthermore, 95 tests were performed on a smaller scale in a flume of 30 m length with a sand layer of 0.8 m height. Pore pressures were measured in the sand at the bottom and wall of the flume and the position of the slope was measured continuously. The tests were performed using very loosely packed sand (close to or less than the minimum density) and therefore all slides that were evoked during the tests were liquefaction type slides. Apparently only in sand with a density close to the minimum density such liquefaction flow slides occur (De Groot et al, 2012). It could be calculated with the equations presented by Van Rhee and Bezuijen (1998), that the height of the slope (equal to the thickness of the sand layer) even in the larger scale tests is still too small for the breaching mechanism to create flows with a gentle slope angle. This was proven in some of the tests (with a slightly more densely packed sand) that resulted in slope angles just below the friction angle of the sand.

4.3 Selection of the physical model

In these tests the final slope depends on the sand discharge that increases with increasing slope height. Therefore small scale tests will result in final slopes that are steeper than in the slopes realized in large scale tests. Therefore a controlled field test is envisaged. According to the theory described in Van Rhee and Bezuijen (1998) a slope with a height of more than 10 m is necessary to find slope steepness's in the order of 6 degrees or less as is measured in the field (Silvis and Groot de 1995). On a smaller scale the breach does not produce sufficient sand-water mixture to create the necessary erosive force for such gentle slopes.

In principle it should be possible to perform a centrifuge test to study the sand-water mixture flow mechanism described in this section. However, for scaling reasons, it would be necessary to use a high viscosity liquid as pore fluid. Without further research it is not known how such a high viscosity liquid influences the flow properties of a sand-water mixture. More fundamental research will be necessary before a geotechnical centrifuge can be a useful tool as it is in other areas of geotechnics.

5 CONCLUSIONS

The choice of physical models has been discussed for various research projects with respect to dike safety. The results show that various problems ask for different physical models. It appeared that in these projects scaling is quite often rather difficult leading to the need for relatively large models. Remarkably, for only one of these projects a geotechnical centrifuge was chosen as the physical model tool of preference. This has several reasons. For macro stability it concerns the heterogeneity in the soil layers. For piping, the scaling effects do not depend on stresses but on geometry. Flow slides can in principle be studied in a centrifuge, however, requires more fundamental knowledge on the scaling rules for eroding sand-water mixtures.

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