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LESSONS LEARNED FROM A FULL-SCALE DYKE FAILURE TEST

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ABSTRACT

A full-scale failure test has been performed on an old river dyke in the Netherlands, to determine its actual strength against failure due to the uplift mechanism and to validate the Van model for the stability analysis of dykes prone to uplift induced failure. The test has been a success and clearly showed the relevance and significance of the uplift mechanism. In combination with earlier verifications, the Van model was found to be suitable, which has already lead to significant reductions on dyke reinforcement projects. The large gap between the actual strength and the calculated strength was confirmed. This gap appeared to be partly necessary because of the large variation in the results of dyke stability analyses by different geotechnical consultants. For the near future, the test may serve as an important benchmark for the development of a more rationally based safety philosophy.

INTRODUCTION

Since the early middle ages in the Netherlands dykes were built to protect the hinterland from flooding. The design of these dykes was based on experience and on the principle of trial and error. Dykes were reinforced or heightened as a consequence of an observed loss of stability or higher storm surge levels. In the last 50 years, the knowledge of the extreme hydraulic conditions and of the different mechanisms which lead to the failure of a dyke has been increased considerably. Nevertheless, it is still complicated to determine the strength of dykes, in particularly of existing dykes.

In 1993 and 1995 the Netherlands were startled by extremely high water levels in the rivers. In the Meuse valley, the inhabitants experienced a lot of problems and substantial damage. The dykes along the river Rhine withstood the high floods of 1995, although at several locations failure was predicted by the state-of-the-art calculation models at that time. Partly based on the advice of geotechnical specialists, over 200,000 people were evacuated to safer grounds as a precautionary measure. However, during the high water period of 1995 hardly any of the dykes deformed seriously.

Hence, a discussion on the actual strength of dykes was started, which led to several recommendations. Special attention was paid to the strength parameters of the dykes in the current approach to safety, and to phenomena related to the loading side. For instance, the expected changes in the global climate are such that the sea level will rise further. In the past century, the sea level has risen about 20 centimetres, while for this century a further rise by about 60 centimetres is expected. At the same time, the Netherlands subside. In the low-lying parts of the country, soil subsidence up to 2050 is expected to range between 2 and 60 centimetres. Furthermore, the fluctuations in river discharge are expected to increase by about 40% in the same period, while the chances of heavy storms and high precipitation increase as well.

In 1995, the decision to evacuate flood endangered areas was, for the geotechnical part, mainly based on predictions using slope stability models like Bishop's simplified model. The heterogeneity of the soil and the discrete nature of in-situ soil investigations result in a fairly large uncertainty in these calculations. As usual in engineering, safety margins are applied to compensate for this uncertainty. As a result, the

Fig. 1. Test site at Bergambacht.

actual strength of a dyke tends to be larger than the calculated strength, especially in case of old dykes.

Normally, it is impossible to perform failure tests on real dykes, due to the large risks involved. A few years ago however, the unique possibility to perform a failure test on a real dyke arose at a location along the river Lek, at about 30 kilometres east of Rotterdam, near the village of Bergambacht. Due to local widening of the river bed, in order to decrease the water level during extremely high water (by 7 millimetres) a new dyke was built behind the existing dyke, as shown in Fig. 1.

The old dyke, first constructed about eight centuries ago, had a height of about 5 metres above the level of the protected area. The subsoil consists of about 12 metres of various peat and clay layers on top of a thick sand layer. In this sand layer, the pore pressures are strongly influenced by the river level. As a result, this dyke is prone to uplift induced failure. The situation is typical for many dykes in the Western part of the Netherlands, where the uplift mechanism is the governing failure mechanism for about 50% of all dykes. This explains the significance of a full-scale dyke test aiming at uplift induced failure.

In this contribution, first the uplift mechanism is explained, followed by a description of the failure test. Next, the conclusions drawn from the test are discussed, followed by the impact of this test on the current engineering practice.

UPLIFT MECHANISM

Mechanism

The uplift failure mechanism, which is a special case of a slope stability problem, is primarily caused by the loss of shear strength at the bottom of the soft layers underneath and behind the dyke, as a result of high pore pressures in the underlying sand layer. The effective contact stresses at the interface between both layers eventually decreases to zero,

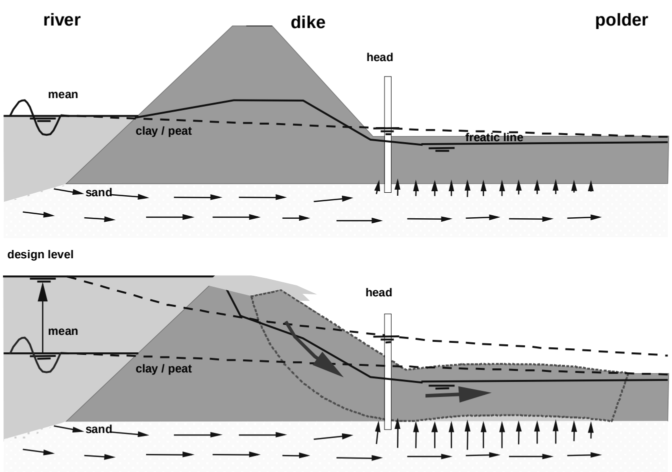

Fig. 2. Uplift induced dyke failure.

giving rise to uplift of the soft layers and sliding, as indicated in Fig. 2. This mechanism mainly occurs in tidal river basins.

Only a few case histories of dyke failure due to uplift have been published, viz. a failure near Dartford, England during the 1953 storm surge (Cooling and Marsland, 1953; Marsland, 1961) and a failure near Streefkerk, Netherlands in 1984. This failure was caused by a combination of moderately high water and dyke reconstruction works (Bauduin *et al.*, 1989). It is conceivable that the initiating mechanism has not been recognised in other cases of dyke failure actually caused by uplift, either because of the resulting damage or because of ignorance about this mechanism.

Another reason for the very few number of known case histories may be the fact that this mechanism is dominant only if the dyke is high enough to withstand other failure mechanisms like overtopping and shallow slope failure. In the lower parts of the Netherlands, the uplift phenomenon turns out to be the dominant failure mechanism for the majority of the dykes if the rather high design water levels are applied. With increasing water levels in the future, the importance of this mechanism will only increase. For historical water levels, generally other mechanisms are dominant.

Modelling of uplift

When the significance of the uplift mechanism became clear, it was soon realised that the existing models used to determine the stability factor of a dyke were not appropriate in case of uplift conditions. These models were all based upon Bishop's simplified method using a circular slip surface (Bishop, 1955). As a result, the zone in which the shear stresses are reduced most is hardly included in the analysis.

A suitable model for stability analyses for dykes prone to uplift induced failure has been presented by Van (Van, 2001; Koelewijn and Van, 2002). A principal sketch of the model is given in Fig. 3. For R_1=R_2 and L=0 the method is equal to Bishop's method. Therefore the approach is consistent with a model which has turned out to be accurate in practice in cases where the slip surface is indeed more or less circular, while in the more general case, some of the geometrical limitations of Bishop's method are relaxed.

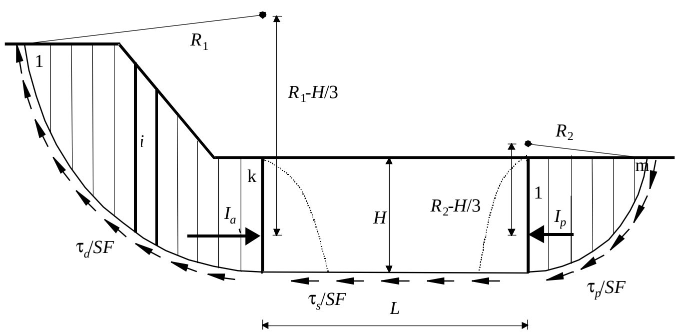

Fig. 3. Van's method.

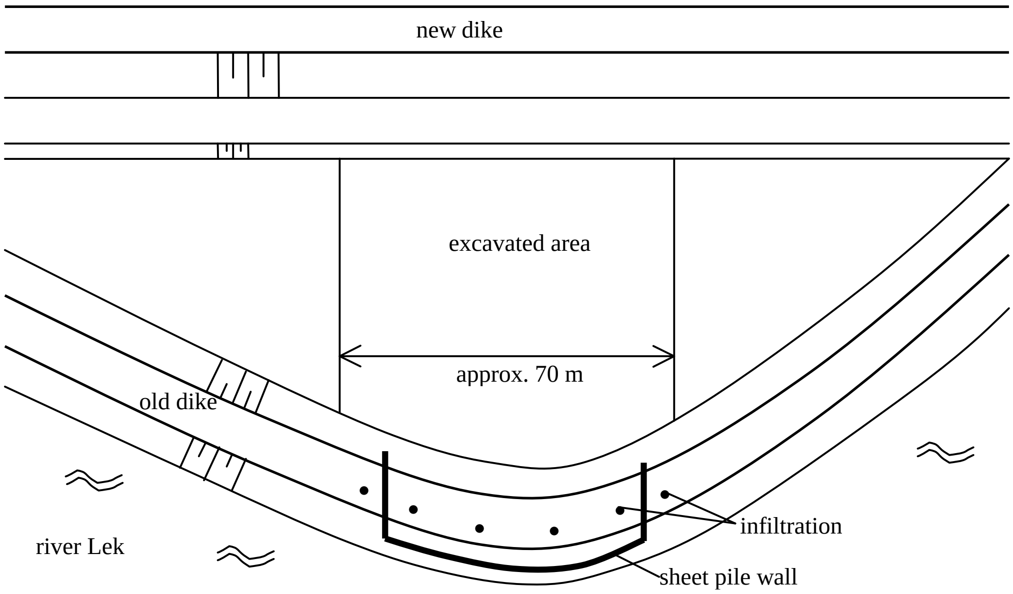

Fig. 4. Plan of the test site.

<u>Centrifuge modelling</u>

After the failure at Dartford, several centrifugal models have been developed to study the influence of uplift pressures on the stability of a flood bank, as summarized by Padfield and Schofield (1983). Recently, more exentensive qualitative tests were performed in the small centrifuge of Delft University of Technology (Allersma and Rohe 2001). The results of these tests were used to perform two quantitative tests in the large centrifuge of GeoDelft, as a preparation for the field test at Bergambacht.

In Table 1, the results of postdictions of the large centrifuge tests with Bishop's method, Van's method and Plaxis are given. The results of these calculations are normalized with reference to the results of the respective centrifuge test – in the first test, failure occurred at an acceleration of 75g (g = gravitational acceleration), in the second test at 100g.

Table 1. Comparison of centrifuge tests with Bishop, Van and Plaxis (Brassinga and Bezuijen, 2001).

Test	Bishop	Van	Plaxis
Test 1 (75g)	1.15	1.00	0.81
Test 2 (100g)	0.93	1.03	0.89

FULL-SCALE FAILURE TEST AT BERGAMBACHT

<u>Design of the test</u>

A plan of the test site showing both dykes is given in Fig. 4. The distance between the toe of the old dyke and the berm of the new dyke is at most 70 metres. The height of both dykes is about 5 metres above ground level. The subsoil in this area generally consists of about 12 metres of various clay and peat layers, but behind the old dyke also a clayey sand layer is found at a depth of 8 to 10 metres. The pore pressures in this layer and in the thick sand layer underneath are strongly influenced by the river level. At normal discharges, the river level is about ground level during low tide and about 1.20 metre higher at high tide.

To raise the phreatic level in the old dyke, a sheet pile wall with a length of 50 metres has been placed at the river side of the old dyke. This has been filled six weeks in advance of the first test. Meanwhile, four infiltration wells were installed on top of the old dyke. The other two wells of the original design were cancelled for budgetary reasons, taking the risk that the whole test would fail if any of the wells would not function properly.

To facilitate the uplift mechanism to occur, the upper two metres behind the old dyke have been excavated over a length of 70 metres about four weeks before the test. The presence of the clayey sand layer, which is rather uncommon in this area, reduced the possibility of uplift because of the relatively high volumetric weight of this layer. However, the excavation increased the risk of an untimely failure as a result of uplift due to the pore pressures in this clayey sand layer at spring tide in combination with a high river discharge. The margin between the lower bound stability factor and the calculated mean stability factor was such that this risk had to be taken – note that this knowledge gap was the main reason to perform the test.

In order to create a more or less two-dimensional situation and to reduce the influence of the sheet pile wall, a screw auger has been used to loosen the soil just within the side parts of the sheet pile wall, about one week before the start of the test.

According to the original design, during the spring tide in mid-September 2001, river water was to be infiltrated into the deep sand layer for about four hours, to cause uplift to occur.

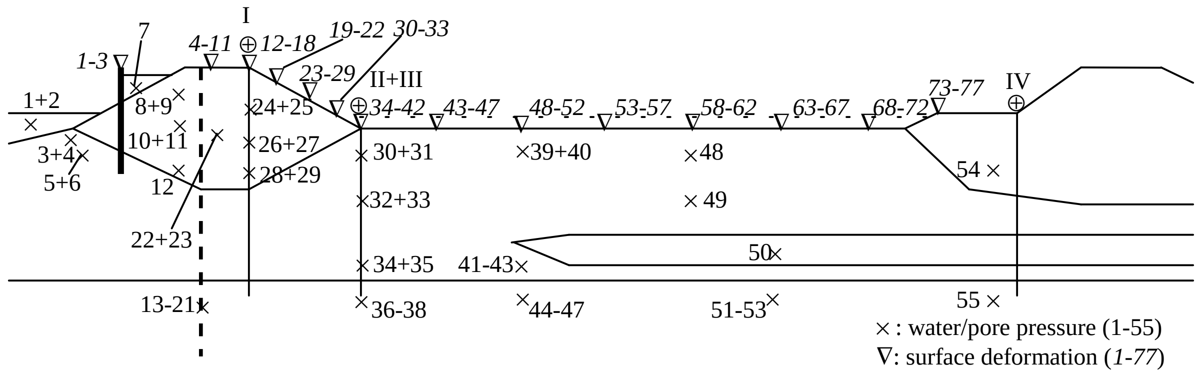

Fig. 5. Instrumentation for the final test.

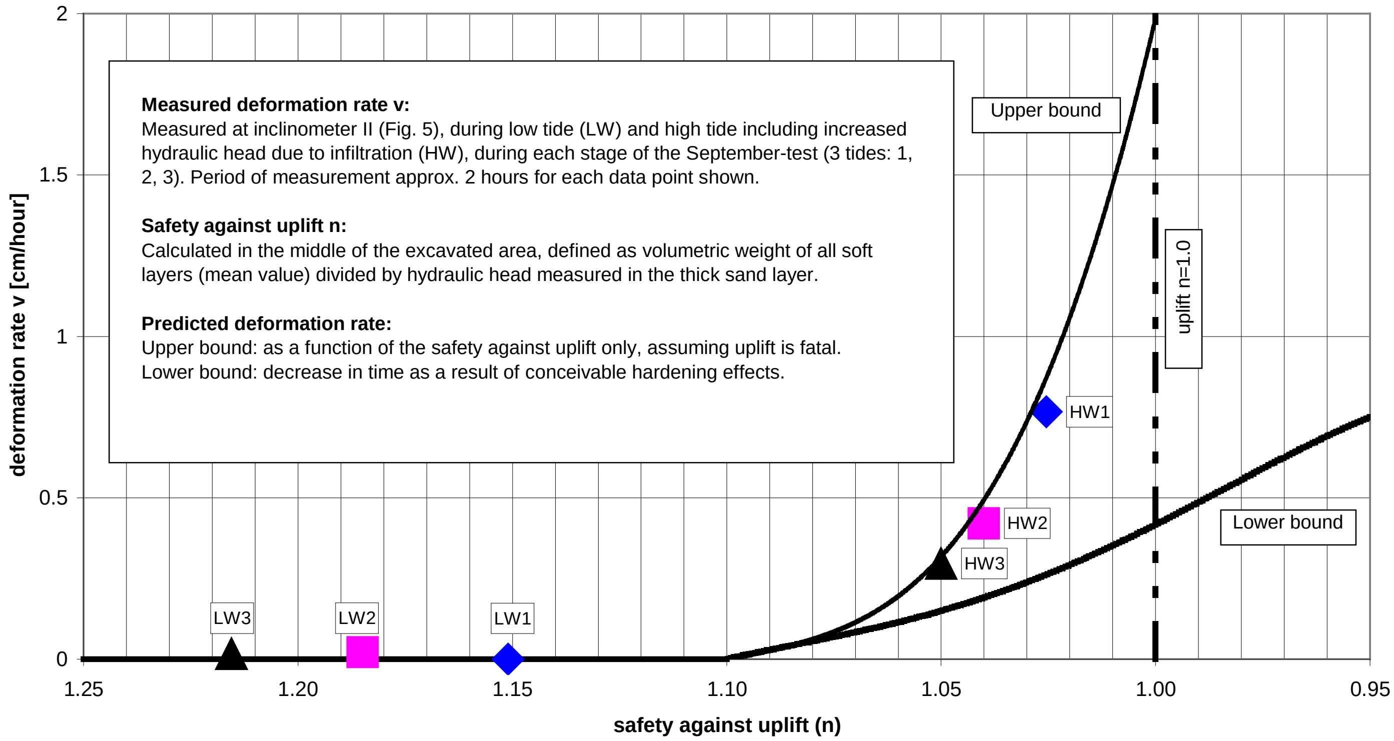

Fig. 6. Deformation rate against uplift safety, as measured in September.

In combination with the raised phreatic level in the core of the old dyke this was supposed to simulate high water conditions as good as possible. During the next low tide a surcharge consisting of about 150 concrete blocks of one cubic metre each was to be placed on top of the old dyke in case the first high tide would not lead to failure. Two other attempts were planned during the next two high tides, after which at least the start of failure should have occurred, with a deformation of at least 20 centimetres.

Monitoring system

For the design of the monitoring system, first an analysis was made of all possible failure mechanisms and possible countermeasures. Totally, twelve potential failure mechanisms were identified, including ‘no failure at all’ and ‘failure of the infiltration system’. This was thought to result in delay of the test. As a countermeasure, more infiltration capacity was foreseen. The projected monitoring was mainly clustered into three cross-sections, distributed evenly along the main test area with a width of 50 metres. Outside these cross-sections some additional monitoring was planned, to cover wider-spread phenomena. Of course, the monitoring was concentrated on the uplift mechanism. The design of the monitoring system has been described more in detail in Koelewijn and Van (2003).

The instrumentation finally used is shown in Fig. 5. It consists of 55 water and pore pressure meters, each with a sampling frequency of once every two minutes, four inclinometers and one extensometer (at location I in the figure) with the same sampling frequency, one total station to measure surface deformations and covering 57 points distributed over the

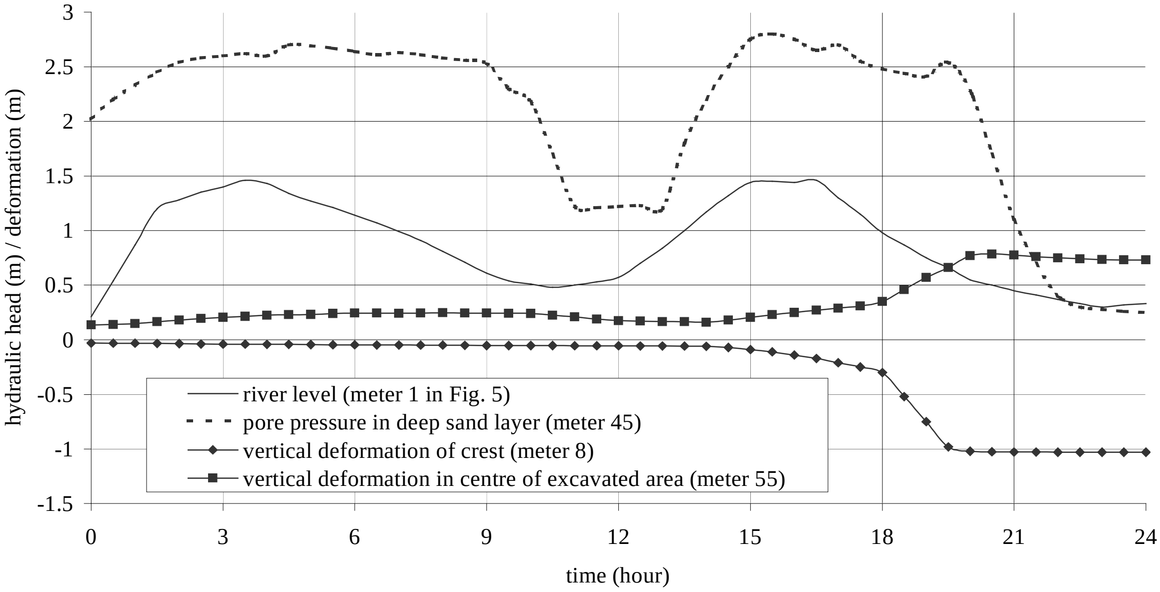

Fig. 7. Main measurements during day of dyke collapse.

whole test area with a sampling frequency of ten to fifteen minutes, and an image processing system covering the landside slope of the old dyke, with four rows of five markers each and a sampling frequency of once every 10 seconds.

Preparations

The preparations in the field mainly went according to the plan. However, when the excavation of the area between both dykes was in progress, during one of the regular visual inspections of the old dyke cracks were found in the asphalt of the old road on top of this dyke. The excavation was temporarily stopped and according to the plan the water level within the sheet pile wall was lowered, after which crack growth decreased. All evidence available indicated that due to both the excavation and the higher freatic line in the core of the dyke, a rather superficial sliding of the old dyke had started. Excavated material was replaced at the first seven metres behind the toe of the old dyke. Quickly made slope stability calculations indicated that this berm would be sufficient, while the stability factor for the desired uplift mechanism would increase about 5% only. In course of time, it turned out that this measure was indeed sufficient, as the cracks remained stable afterwards.

First test: September 2001

The first stage of the test started on the 17th of September. During the first high tide about 80% of the capacity of the infiltration wells was used and the old dyke came at the brink of failure: at surface deformation meter 55 (Fig. 5) an upward displacement of 140 millimetres was recorded, while inclinometer II showed a displacement towards the new dyke of about 20 millimetres near the bottom of the soft layers and the crest of the old dyke settled slightly. The upward movement of the excavated area was most probably caused by the beginning of uplift.

The next morning, during the second high tide two of the infiltration wells clogged and the maximum pore pressures in the deep sand layer were a bit lower than during the first high tide. In spite of the surcharge, the deformation rate was smaller than the day before. Regeneration of the clogged wells during the following low tide was not successful enough: during the third and last attempt, the pore pressures in the deep sand layer were lower again.

In Fig. 6 the deformation rate below the toe of the old dyke during the various stages of this test is shown against the safety against uplift in the centre of the excavated area, indicating that the deformation rate strongly depends on the safety against uplift.

During the first high tide the beginning of piping occurred at several locations in the excavated area. The next day, even at low tide with the infiltration wells turned down for hours already, water with gray sand and pieces of peat continued to flow through these wells. Nonetheless, failure did not occur.

Final test: November 2001

The data collected during the first test was considered to be very useful, yet the old dyke had not collapsed. Within two weeks sufficient budget was found for a restart of the test, this time with a total of nine infiltration wells and using prefiltered water from a nearby drinking water pre-filtration station, instead of raw river water. This final test started on Monday, November 26th, 2001 and would last at most until the next Friday. Instead of infiltrating only for a few hours during high tide, this time a more continuous infiltration scheme was planned, to simulate the length of a flood from upstream better and to check several assumptions on time-dependent effects on the safety of dykes, like the penetration of a high hydraulic head from the sand layers into the clay and peat layers.

During the first two days of the test, with an achieved safety against uplift between 1.01 and 1.10, the deformations were comparable to those in September, cf. Fig. 6. In this period already three infiltration wells failed, probably as a result of the deformations which had already started.

In the afternoon of the third day, around half past three the maximum hydraulic head underneath the old dyke and the excavated area was reached, with a calculated safety against uplift of about 0.95. At this point the deformation rate increased strongly with a further increase after another few hours when the pore pressures were somewhat lower again. As shown in Fig. 7, deformations of the old dyke of over one metre occurred. The extent of the failure was much larger than expected: 110 metres instead of 50 metres only. As a result the image processing system failed, as the cameras stood within the area of the slide. Figure 8 shows the collapsed dyke. To the left in this picture the risen part of the excavated area is clearly visible.

Fig. 8. Dyke failure due to uplift mechanism.

MAIN FINDINGS OF THE TEST

It can be concluded that the failure test on the old dyke near Bergambacht has been a success. The aim of the test was to investigate the uplift mechanism as an introduction to flooding. During the first test in September the start of movement of the dyke was observed and on the 28th of November failure occurred in rather close agreement with the predictions – except that the width of the failure was much larger.

Initially, before September, with the Van-model a stability factor of 1.25 has been calculated using mean values for all parameters, assuming an infiltration period of four hours, i.e. with a non-stationary groundwater situation. Using lower bound parameters a stability factor of only 0.9 was calculated, therefore the uncertainty about the moment of failure was considerable. In October a new prediction was made, using information on the approximate location of the clayey sand layer and the permeability of the different layers gathered during the September-test. When applying the pore pressures as measured at the start of failure (November 28th, at 15:30) in this calculation, leaving the geometry and the (mean value) strength parameters unchanged, a stability factor of 1.02 is found using the Van model, i.e. 2% unsafe. This result appeared to be very sensitive to the volumetric weight: a small difference in the weight applied for the various soft layers easily leads to difference of 10% (Bishop's model and Spencer's method (Spencer, 1967) are found to be equally sensitive in this case). The results confirm the practical value of the Van model for the analysis of the stability of dykes prone to uplift induced failure. From comparative analyses with the Plaxis finite element code and with Bishop's method, and from the aforementioned centrifuge tests, it had already been concluded that a model factor of 1.05 would be appropriate (Van, 2001) – this has now been confirmed by this (single!) field test.

The safety margin between the actual strength and the strength calculated according to the regular Dutch procedures on dyke design and evaluation proved to be very significant. Back-calculations indicated that the pore pressure in the deep sand layer at the start of failure would normally be reached with a river level of 4.70 metres above ground level, i.e. 0.5 metre below crest level. However, the calculated critical level has been found to be about 2.50 metres above ground level only, while the present design level is 3.60 metres above ground level (therefore, the old dyke had been declared unsafe).

Apart from variation of the subsoil and shortcomings of the calculation models used, a good reason to retain some margin between the (usually unknown!) actual strength and the calculated strength lies in the variability in the results of calculations by different geotechnical consultants: within the scope of the present research, five consultants have been asked to evaluate the stability of the old dyke according to the regular Dutch procedures on dyke evaluation. Their results varied by 25% (Lindenberg *et al.*, 2003).

Because of the rather sudden collapse of the tested dyke, the hope that an early warning system can be based on monitoring the deformations of dykes has proved to be idle. A more positive outcome of this test is the observation that uplift does not necessarily lead to failure: the dyke only collapsed when the safety against uplift as defined in Fig. 6 was significantly below 1.0.

Regarding the width of the failure, it has been concluded that the remoulded shear strength near the sides of the sheet pile wall was too high to allow for a failure with a limited extent. Instead, a failure occurred with much larger side wedges and a less sharp transition between the collapsed and the undamaged part of the dyke. This has been confirmed by three-dimensional stability analyses made afterwards.

IMPACT ON CURRENT ENGINEERING PRACTICE

The impact of the test and the related research on the current engineering practice has been such that the costs have been recoverd several times already. This is mainly related to the use of the Van model for uplift situations: with this validated model, a net increase of 3 to 5 percent of the calculated stability factor is achieved, which has already resulted in postponing several dyke reinforcement projects (due to the increasing design levels because of climate changes, eventually reinforcement and heightening of most dykes in the Netherlands will be inevitable).

In villages where dyke reinforcement becomes necessary, the use of three-dimensional analyses incorporating the influence of the side wedges of the sliding plane on the overall stability may prevent demolition of houses, windmills and other monuments, while with the present approach using two-dimensional analyses only, usually very costly measures need to be taken to protect such monuments.

In the years to come, a more rationally based safety philosophy needs to be developed. The well-instrumented test at Bergambacht may serve as an important benchmark to this new safety philosophy.

ACKNOWLEDGEMENT

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REFERENCES

Allersma, H.G.B. and A. Rohe [2001]. "Centrifuge tests on the failure mechanism of dykes", *Proc. Fourteenth Southeast Asian Geot. Conf.*, Hongkong, pp. 1077-1081.

Bauduin, C.M.H., C.J.B. Moes and M. van Baalen [1989]. "The influence of uplift water pressures on the deformations and stability of flood embankments", *Proc. Twelfth Intern. Conf. on Soil Mech. and Found. Eng.*, Rio de Janeiro, Vol. 3, pp. 1713-1716.

Bishop, A.W. [1955]. "The use of the slip circle in the stability analysis of slopes", Géotechnique, Vol. 5, pp. 7-17.

Brassinga, H.E. and A. Bezuijen [2001]. "Opdrijfmechanisme rivierdijken – analyse van resultaten centrifugeproeven (Uplift mechanism river dykes – analysis of results of centrifugal tests)" [in Dutch], report no. CO-710301/203, GeoDelft, Delft.

Cooling, L.F. and A. Marsland [1953]. "Soil mechanics studies of failures in the sea defence banks of Essex and Kent", *Conf. on the North Sea Floods of 31st January – 1st February, 1953*, London, Inst. Civil Eng., pp. 58-73.

Koelewijn, A.R. and M.A. Van [2002]. "Stability analysis for embankments prone to uplift induced failure", in *Numerical Models in Geomechanics – NUMOG VIII*, (G.N. Pande and S. Pietruszczak, eds.) Swets & Zeitlinger, Lisse, pp. 561-564.

Koelewijn, A.R. and M.A. Van [2003]. "Monitoring of the test on the dike at Bergambacht: design and practice", *Proc. Thirteenth European Conf. on Soil Mech. and Geot. Eng.*, Prague, *in print*.

Lindenberg, J., M.Th. van der Meer, B.A.N. Koehorst and A.R. Koelewijn [2003]. "Stabiliteitstoetsing van dijken: een eenduidige zaak? (Evaluation of dyke stability: an unambiguous case?)" [in Dutch], Geotechniek, Vol. 7 (2), pp. 46-52.

Marsland, A. [1961]. "A study of a breach in an earthen embankment caused by uplift pressures", *Proc. Fifth Intern. Conf. on Soil Mech. and Found. Eng.*, Paris, Vol. 2, pp. 663-668.

Padfield, C.J. and A.N. Schofield [1983]. "The development of centrifugal models to study the influence of uplift pressures on the stability of a flood bank", Géotechnique, Vol. 33 (1), pp. 57-66.

Spencer, E. [1967]. "A method of analysis of the stability of embankments assuming parallel interslice forces", Géotechnique, Vol. 17, pp. 11-26.

Van, M.A. [2001]. "New approach for uplift induced slope failure", *Proc. Fifteenth Intern. Conf. on Soil Mech. and Found. Eng.*, Istanbul, Vol. 3, pp. 2285-2288.