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Small- and full-scale test programme on uplift induced slope failure

Programme d'essais à petite et à grande échelle sur l'instabilité des pentes induite par le soulèvement de la couche imperméable

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ABSTRACT: Sub soil stratum in deltaic regions typically include a succession of permeable and non-permeable layers. Consequently, dikes built to protect delta areas, should be able to resist not only extreme surface water levels, but also an increase in hydraulic head in permeable layers. The rise in hydraulic head might result in uplift of the cover layer, inducing either backwards erosion piping or slope stability. A large research programme, including the combination of numerical analysis, centrifuge testing and field trials, is started to study the uplift phenomenon. Preliminary results show that uplift has a clear influence on dike stability. Horizontal compression of the cover, during uplift, might trigger slope failure. Large cracks in uplifted cover layer were not found in the field trials, although some local failure, resulting in sand boils, was observed. The test results provide valuable experimental data to further validate numerical tools and stability assessment procedures.

RÉSUMÉ: La stratification du sous-sol dans les régions deltaïques comprend généralement une succession de couches perméables et non perméables. Par conséquent, les digues construites pour protéger les zones deltaïques doivent pouvoir résister non seulement à des niveaux d'eau extrêmes, mais aussi à une augmentation des charges hydrauliques dans les couches perméables. L'augmentation de la charge hydraulique peut entraîner un soulèvement de la couche imperméable, induisant soit une érosion régressive, soit une instabilité des pentes par glissement rotationnel. Un programme de recherche, combinant des analyse numériques, expérimentations dans une centrifugeuse et expériences de terrain, a été lancé pour étudier le phénomène de soulèvement. Les résultats préliminaires montrent que le soulèvement exerce une influence évidente sur le glissement rotationnel des digues. La compression horizontale de la couche imperméable, pendant le soulèvement, semblerait déclencher le glissement rotationnel. Les expériences de terrain n'ont pas révélé de grandes fissures dans la couche imperméable une fois soulevée, bien que certaines ruptures locales, comme des bouillonnements, aient été observées. Les résultats expérimentaux fournissent des données précieuses pour valider davantage les outils numériques et les procédures d'évaluation du glissement rotationnel.

Keywords: Stability; experimental soil mechanics; uplift.

1 INTRODUCTION

Typically, hydraulic loads on water retaining constructions during design conditions not only include the free water acting on the dike body, but also changes in pore water pressures in sub soil layers. Figure 1 shows a classical case in which, due to a hydraulic connection between a sand layer and the free water, the hydraulic head increases until uplift of the non-permeable cover layer occurs, which reduces the slope stability. Moreover, due to uplift the cover layer might break, starting erosion of the sand layer: backward erosion piping.

In deltaic regions, subsoil stratification often contains a succession of permeable and non-permeable layers. As such, depending on design load conditions and dimensions of the dike, the typical deltaic subsoil is in principle susceptible to uplift.

Several studies have been conducted to show how the uplift phenomenon should be accounted for in stability assessment of dikes, Marsland & Cooling (1953), Marsland (1988), Van et al. (2005).

These studies assume that for uplift conditions the cover layer remains intact. Some guidelines on dike stability assessment (TAW, 2001) hypothesize that thin cover layers, < 4 m, will break and lose their integrity during uplift. Consequently, in these guidelines, the cover layer is assumed to have no strength under uplift conditions.

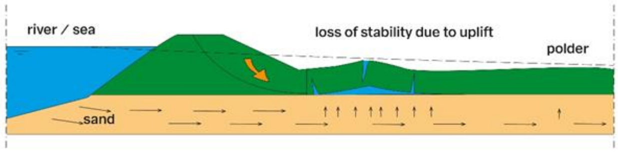

Figure 1. Sketch of slope instability due to breaking of the cover layer due to uplift.

Although local failure of the cover layer by cracks that result in sand boils and facilitate backward erosion piping, are regularly found (a.o. Bezuijen, 2017), field cases in which the cover layer completely loses its integrity, inducing slope failure, are not known to the authors.

Climate change and the corresponding sea level rise will result in a more frequent occurrence of the uplift mechanism. At the same time, the increase in urbanisation of deltaic areas will reduce the available space for dike reinforcement. Consequently, the uplift phenomenon needs to be properly understood to face future challenges in flood protection.

The study aims for generating experimental data and validate existing numerical tools for stability assessment of dikes. To maximise impact, the study includes numerical simulation, centrifuge testing and field trials. The centrifuge testing allows to study the impact of varying relevant parameters, like the thickness of the cover layer or cover layer properties under controlled and simplified conditions. A field trial includes all relevant uncertainties but is only related to the specific geometry and soil conditions at the test site. The combination of scale modelling and field trials allows for checking on possible scale or schematisation effects which might be incorporated in centrifuge modelling. Vice versa, scale modelling helps in generalising the results from the field trials.

2 NUMERICAL ANALYSIS

A numerical study employing advanced finite element analyses, Visschedijk (2020), showed 4 different potential failure mechanisms under uplift conditions, see Figure 2. In mechanism *a* uplift does not influence failure, resulting in a circular sliding plane. Mechanism *b* includes the uplifted zone and a passive failure plane. Mechanism *c* describes buckling of the cover layer, resulting in loss of integrity. Mechanism *d* shows horizontal compression of the cover layer followed by slope instability.

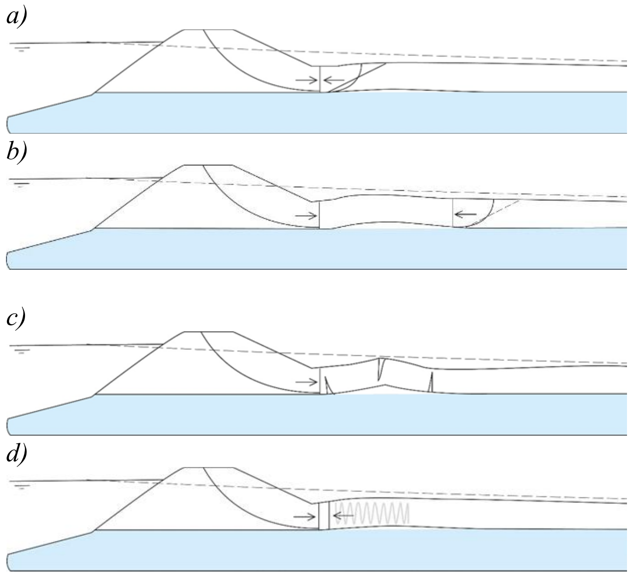

Figure 2. Sketch of the 4 different failure mechanisms observed in the numerical analysis, after Visschedijk (2020).

Mechanism *a* and *b* allow for stability assessment by Limit Equilibrium Methods, as shown by Van et al., (2005). For the few cases in which slope failure due to uplift was found in the field, no passive failure plane could be observed. This makes it difficult to distinguish between mechanisms *b* and *d* for field conditions.

The numerical analysis predicts mechanism *c* only for specific conditions, i.e. a thin cover layer < 2 m with large stiffness, Young's modulus > 3 MPa and high permeability in the sand layer to maintain the uplift pressure during deformation of the cover layer.

Mechanism *d* is dominated by the interaction between slope stability and horizontal compression of the cover layer. An unstable slope induces a horizontal compression on the cover layer, which increases when the cover layer is lifted. Further compression of the cover layer will induce displacements along the active part of the sliding plane. Depending on the material of which the dike is constructed, these deformations might start progressive failure, when locally the peak strength is exceeded.

The numerical analysis showed that mechanism *d* was the decisive mechanism for cover layer thicknesses up to 4 m. A numerical analysis, using PLAXIS 2D v22, was performed to get more understanding of this mechanism.

Figure 3 shows the horizontal displacements found at uplift of the cover layer. The geometry contains a dike with height 6 m, and slope 1(V): 2.5 (H). The cover layer thickness is 3 m and is followed by a 12 m thick sand layer. The Mohr-Coulomb model is used to model soil behaviour. Table 1 gives the relevant parameters. An interface, with the same strength characteristics as the surrounding soil, was applied between the cover layer and sand layer to obtain a discrete shear plane. For this geometry, the maximum horizontal displacement is in the order of 0.17 m.

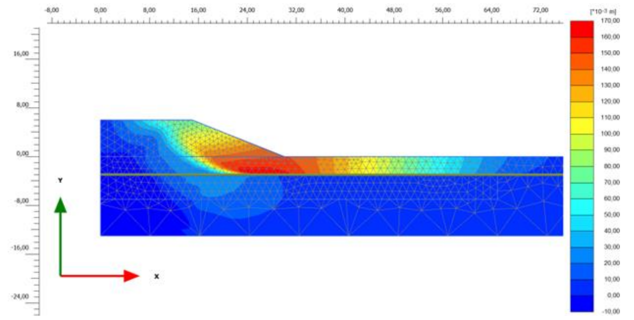

Figure 3. Horizontal displacements under uplift conditions.

Table 1. Soil properties for numerical simulations.

parameter	unit	dike	cover layer	sand
vol. weight, γ^*	[kN/m^3]	17	17	18
cohesion, c'	[kN/m^2]	18	18	0
friction angle, φ'	[°]	0	0	32
Young's modulus, E	[MN/m^2]	3	3	10
Poisson's ratio, ν	[-]	0.3	0.3	0.3

* equal for saturated and unsaturated conditions

3 CENTRIFUGE TESTS

A series of 13 centrifuge tests has been conducted. Details of the tests are presented by Cengiz et al. (2024). The tested model contains a sand layer, a clay cover layer and dike body build from sand. Uplift was activated at 80g after which the g-level was increased further to reach failure.

Figure 4 shows the horizontal displacements in the cover layer for a typical failure found in the test series. The horizontal displacements are assessed from the test results by Particle Image Velocimetry, PIV analysis. The observed mechanism complies well with the numerical results shown in Figure 3.

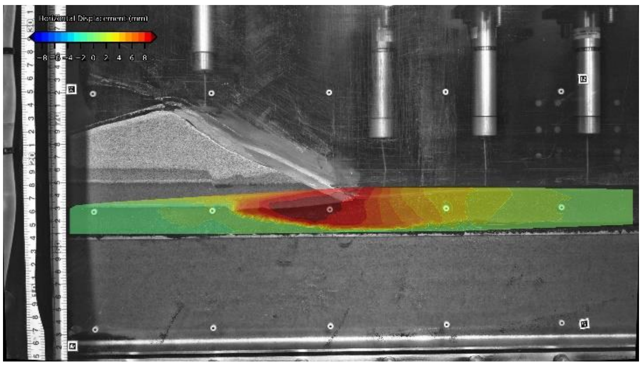

Figure 4. Horizontal displacements in cover layer at slope failure, green = 0 mm, red = 8 mm.

4 FIELD TRIAL

The field trial was conducted on a dike section along the River IJssel, near Kampen, the Netherlands. New flood protection works made this dike section redundant and as such available for testing.

The subsoil is divided into a cover layer containing a clay and peat layer followed by a sand deposit. To enhance instability additional measures were taken:

- The dike height was increased by 2.6m.
- At the toe, the soil was excavated by 1.25 m. total slope height was 7.75 m.
- 8 infiltration wells were placed to increase the hydraulic head in the sand layer.
- A drain was placed in the sand core to increase the phreatic level in the dike.
- Clay was added to the dike to prevent local slope instability.
- The slope was changed into 1(V): 2(H)
- A row of 10 containers, which could be filled remotely, was placed on top of the dike.

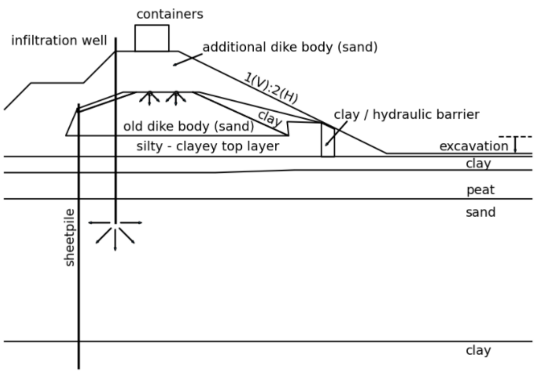

Figure 5. Test set-up, sketch of cross section.

Figure 5 shows the tested cross section. Prior to the main field trial, the uplift of the cover layer was tested in a separate but nearby field. This test showed that 1) the planned infiltration system could lift the cover layer, 2) that the uplift could be maintained for at least 3 days, after which the test was terminated and 3) hardly any leakage occurred despite the instrumentation that was placed in the cover layer or sand layer below.

The instrumentation of the main field trial was placed in three rows, containing 12 pore pressure transducers in the sand layer, 30 in the cover layer, 3 in top layer directly below the dike body, 7 open standpipes to measure the hydraulic head in the dike body, 15 inclinometers to measure horizontal displacements, 9 extensometer measuring vertical deformations at three different depths. Additionally, surface deformation was measured at 96 positions using a total station. Figure 6 presents an impression of the test set-up at the start of the main field trial.

Figure 6. Impression of the main field trial.

5 RESULTS

The test started on Monday 14 August 2023 at 9:00 by stepwise increasing the hydraulic head in the sand layer. Already in the first step the horizontal displacements directly responded to the hydraulic head increase.

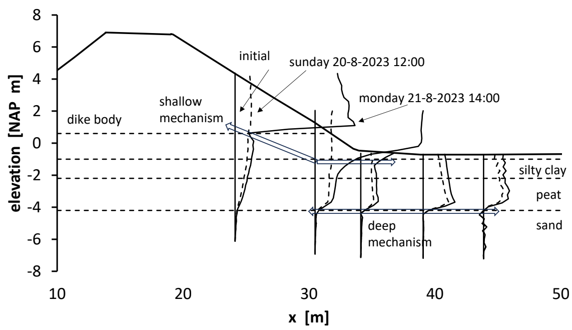

Figure 7. Horizontal displacements during the test.

Figure 7 shows the horizontal displacements measured during the test at the centre cross section. The horizontal displacement measurements at all but the left-most location clearly show a horizontal displacement at the interface of peat and sand. During the test the horizontal displacements developed uniformly over the cover layer thickness. This corresponds to mechanism *d* in Figure 2 and numerical analysis given by Figure 3. At these positions, the horizontal displacements are ranging between 0.05 to 0.10 m.

In the last stages of the test, starting on Sunday 20 August 2023, the last part of the sand core was filled, which caused a shallow failure plane to develop. The three instruments on the left side clearly indicate the position of the shallow sliding plane.

6 CONCLUSIONS

Uplift of a cover layer near the toe of a dike has impact on slope stability. This impact was studied by a combination of numerical analyses, centrifuge testing and a field trial. Analysis of the results is still ongoing. The experimental results clearly show the horizontal displacements which are induced at uplift of the cover layer. The observed displacement field corresponds to the numerical and experimental results, which clearly show that uplift results in horizontal compression of the cover layer.

In contrast to the centrifuge tests, the horizontal compression of the cover layer did not result in a deep failure in the field trial. Instead, the last stage in filling the sand core resulted in shallow failure.

Further analysis of the test results will lead to recommendations on stability assessment for dikes under uplift conditions.

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