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Centrifuge tests on the uplift and deformation patterns of clay cover layers in deltas

Essais en centrifugeuse sur les modèles de soulèvement et de déformation des couches d'argile dans les deltas

C. Cengiz*
Deltares, Delft, The Netherlands

M.A. Cabrera
TU Delft, Delft, The Netherlands

B. Wittekoek, M. Fransen, L. Wopereis, C. Zwanenburg
Deltares, Delft, The Netherlands

**cihan.cengiz@deltares.nl*

ABSTRACT: As the population in cities all over the world is increasing, the effects of climatic action on the resilience of communities is becoming more and more important. Cities situated in deltas are also under strong urbanization demands and these demands have to be met with due consideration of the challenges presented by climate change, land subsidence and sea-level rise. Within this context, the local geological conditions in the Netherlands present a particularly pressing challenge where water pressure under a clay cover may increase. The static equilibrium of the cover layer might be adversely affected, and uplift failure can be imminent. A recent research program into this failure path has been initiated. Besides the field tests and advanced numerical modelling approaches, the research program also made use of centrifuge tests to quantify the extent of uplift, cracking, and deformation phenomena. This contribution intends to exhibit the aspects of the centrifuge tests conducted as part of this study. The experimental setup design and design considerations will be explained as well as the instrumentation methodology and the reasoning behind the instrumentation choices. This contribution aims to improve the stability assessment of dikes under uplift conditions.

RÉSUMÉ: À mesure que la population des villes du monde entier augmente, les effets de l'action climatique sur la résilience des communautés deviennent de plus en plus importants. Les villes situées dans les deltas sont également soumises à de fortes demandes d'urbanisation et ces demandes doivent être satisfaites en tenant dûment compte des défis présentés par le changement climatique, l'affaissement des terres et l'élévation du niveau de la mer. Dans ce contexte, les conditions géologiques locales aux Pays-Bas présentent un défi particulièrement pressant, car la pression de l'eau sous une couverture argileuse peut augmenter. L'équilibre statique de la couche de couverture pourrait être affecté négativement et une rupture par soulèvement pourrait être imminente. Un programme de recherche récent sur cette voie d'échec a été lancé. Outre les essais sur le terrain et les approches avancées de modélisation numérique, le programme de recherche a également eu recours à des essais par centrifugation pour quantifier l'ampleur des phénomènes de soulèvement, de fissuration et de déformation. Cette contribution vise à exposer les aspects des essais de centrifugation menés dans le cadre de cette étude. La conception de l'installation expérimentale et les considérations de conception seront expliquées ainsi que la méthodologie d'instrumentation et le raisonnement derrière les choix d'instrumentation. Cette contribution vise à améliorer l'évaluation de la stabilité des digues en conditions de soulèvement.

Keywords: Dike stability, macro-stability, uplift failure, flood defences, centrifuge testing.

1 INTRODUCTION

In densely populated Dutch delta regions, an unfavorable geological condition is encountered where a thin clay cover is found over permeable layers. While this stratification does not pose significant challenges for most engineering applications, it creates a unique set of issues for dike engineering purposes. The problem is accentuated by large riverbeds and increasing severity and frequency of weather and precipitation extremes. The Dutch dike engineering approach focuses on macro-stability calculations, considering a scenario where the dike stability is lost due to buckling or uplifting of the clay cover. This concern arises when the water pressure within the sand beneath the top layer increases due to rising external water levels. When the water pressure matches the weight of the top layer, it begins to rise or "float". Subsequently, under the influence of horizontal compressive forces, the top layer may experience deformation, potentially leading to buckling or bursting – this is a geometrically non-linear 'second-order' effect –. The expected formation of bending cracks, along with the resulting reduction in the bending capacity, can exacerbate the risk.

To address the risk of bursting, the current assessment and design approach involves a simple rule: for top layers with a thickness of 4 meters or less, no shear strength is assigned when the safety factor is 1 or lower. This particular rule is based on expert judgement without extensive support from calculations, experiments, or empirical data. However, it is widely believed that this approach errs on the side of caution and tends to lead to designs that are overly conservative. The above-mentioned risk is especially pressing in the Eastern part of the Netherlands, where the Holocene top layer is commonly situated on top of a relatively rigid and permeable Pleistocene sand layer. It is plausible that high-water levels in adjacent rivers and estuaries may generate locally high pore pressures directly under or beside a dike. Consequently, the effective normal stresses at the layer interface decrease, eventually to zero, giving rise to uplift and sliding failures (Van et al., 2005). A pictorial description of the problem is illustrated in Figure 1.

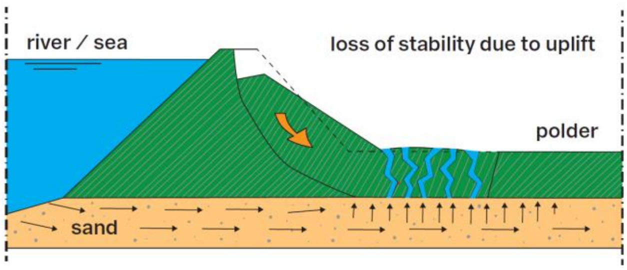

Figure 1. A sketch of buckling or uplifting mechanims over a dike clay cover.

In order to study the dike deformation mechanisms, a series of centrifuge experiments are carried out at the 5 m radius Deltares Geo-Centrifuge. The goal of the experimental program is to better understand the mechanisms that affect the behaviour of the dike and cover layer under extreme water levels. The forthcoming proceeding paper will introduce the experimental methodology and early findings of the experimental program by elaborating on an exemplar test carried out at the Deltares Geo-Centrifuge. It should be noted that centrifuge testing is part of the activities carried out under an overarching project, for a broader description, interested readers are referred to Zwanenburg et al. (2024). This project combines physical and numerical models as well as field experiments.

2 MATERIALS AND EXPERIMENTAL SETUP

Figure 2 illustrates a sketch of the experimental setup together with the soil layers, instrumentation details, and the model-scale dimensions.

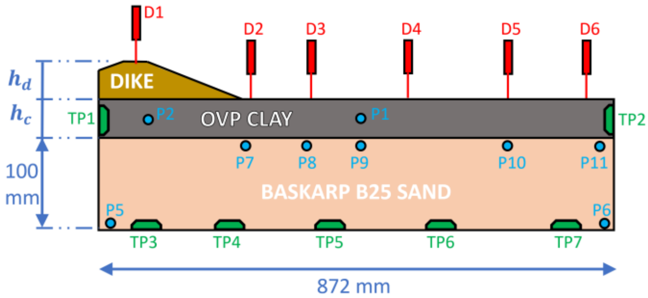

Figure 2. A sketch of the experimental setup.

2.1 Materials

The geo-materials used in the centrifuge model included Baskarp B15 and B25 sands and Oostvaardersplassen (OVP) clay. The model construction commenced with the addition of a precalculated amount of Baskarp B25 in the strongbox to serve as a permeable layer which underlies the cover layer (OVP Clay). The sand is placed by wet pluviation and tamping, achieving a relative density of 90%. Once the placement of the basal sand layer was finalized, remoulded OVP clay slurry was placed on top of the sand, being consolidated with an overburden pressure of 20 kPa within the strongbox and forming the cover layer. Please note that block samples consolidated to 40 kPa were also used in the wider experimental program. Upon completion of consolidation, the sand dike consisted of Baskarp B15 sand, constructed above the cover layer. Further details on the engineering properties of the OVP clay and Baskarp sands can be found in Fern et al. (2017) and Rosenbrand et al. (2022), respectively.

2.2 Experimental Setup

The models are prepared in a strongbox which can withstand the centrifugal accelerations and with a transparent window allowing in-flight image capture for digital image analysis. The width and length of the strongbox is 200 and 872 mm, respectively. The depth of the strongbox is 450 mm. The base plate of the strongbox is instrumented with total pressure sensors, abbreviated as 'TP' in Figure 2. Similarly, additional total pressure sensors are affixed to the side walls, capturing the lateral pressure changes in the cover layer. An array of eleven pore water pressure sensors is distributed over the model, abbreviated as P in Figure 2. Notably, P5 and P6 indicate the pressure head of the influent and effluent flow. P7 to P11 measure the porewater pressure at the sand-clay interface. Finally, P1 and P2 give important insight into the pore water pressure within the OVP clay cover layer. Surface vertical deformations are monitored by six hard sensor points instrumented with DCDTs. These sensors are essentially similar to Linear Variable Differential Transformers (LVDT), but they do not incorporate any spring-loaded system, preventing jamming under the action of a centrifugal acceleration field. Beyond the conventional instrumentation, the deformations are monitored with a camera system, enabling post-testing digital image correlation analyses. Due to the large aspect ratio of the transparent window, a total of two cameras are used for monitoring the entirety of the model. A photograph of the intact dike is shown in Figure 3.

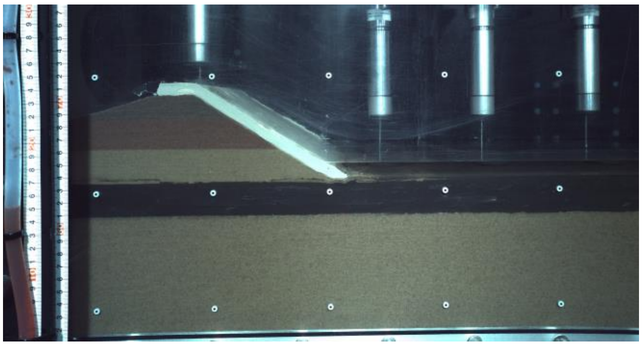

Figure 3. A photograph of the dike before failure occurs (note that a thin layer of Vingerling K147 clay (white) is used as an armor layer to retain water within the dike body).

3 EXPERIMENTAL METHOD

One of the primary objectives of the tests are to see if increments of hydraulic pressure on the riverside would cause uplift failure on the landside. With this in mind, during the centrifuge flight, the experimental assembly allows for adjustment of the hydraulic head on the river side while keeping the landside head constant. The influent flow is supplied from the left-hand-side, see Figure 2, using a series of diffusers. Water is allowed to leave the permeable sand from the right-hand side of the assembly.

The centrifugal acceleration regime applied to the model is illustrated in Figure 4. The hydraulic loading regime necessary to induce uplift is estimated on equivalent finite element calculations, assuming a stress field equivalent to an effective centrifugal acceleration of 80g. The hydraulic loading regime is illustrated in Figure 5, where the difference in influent (P5) and effluent (P6) pressure heads can be seen.

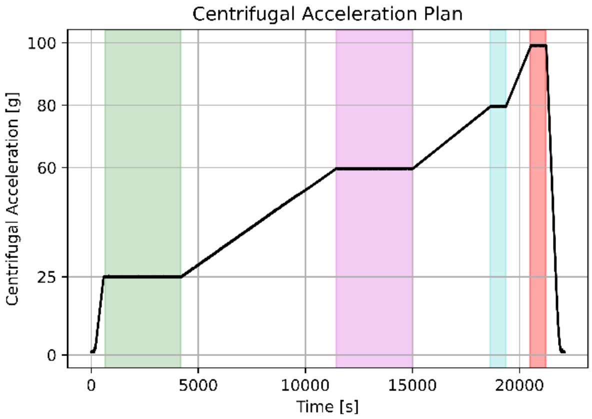

Figure 4. Centrifugal acceleration during the experiment.

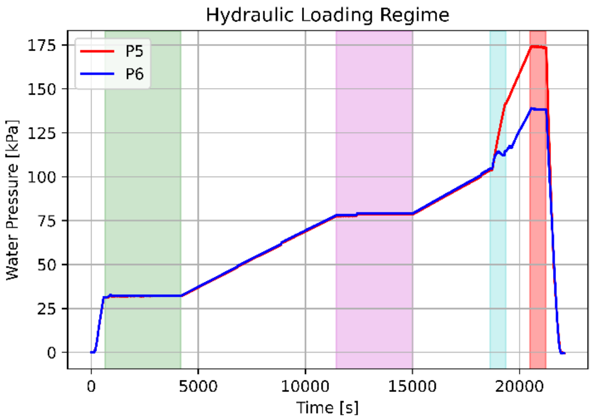

Figure 5. Hydraulic loading regime during the test.

As a result of increasing the hydraulic head difference across the model, uplift of the cover layer is triggered. Vertical displacements measured by the DCDTs are illustrated in Figure 6 (notice that the background coloring in the graph coincides with different phases of the experiment as illustrated in Figure 4 and Figure 5). A photograph capturing the moment of uplift is also shown in Figure 7.

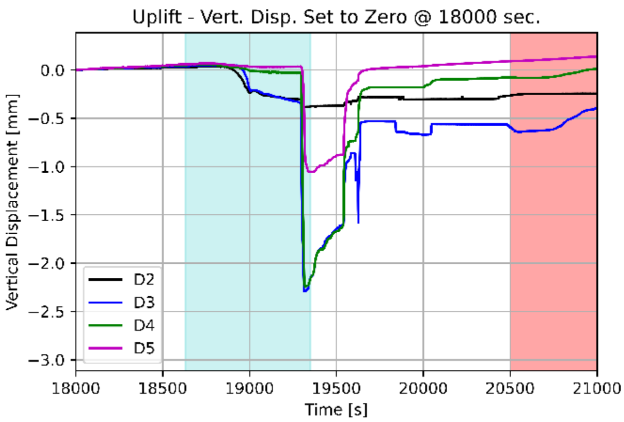

Figure 6. Vertical displacements measured by the DCDTs at the initiation of uplift.

Figure 7. Uplift and separation of the cover layer.

Figure 8 illustrates the overall deformation observed at the end of the test where multiple failure planes within the dike body are visible which also bring about settlements (reduced free-board). In addition to the dike body failure, the cover layer exhibits severe cracks, most notably at the toe. The cracks extend diagonally, and its slope is steeper than that of the dike slope. Multiple wells have also formed as a result of the increased hydraulic heads which reduce the integrity of the cover layer.

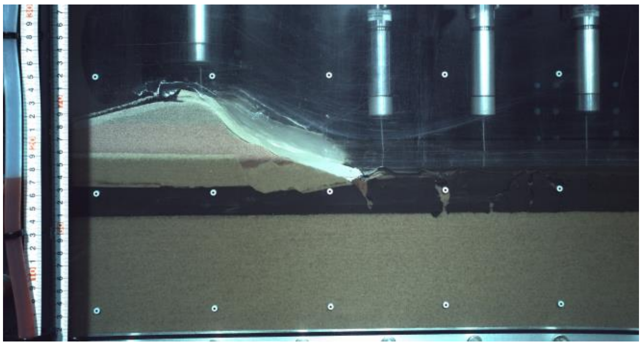

Figure 8. Overall deformation pattern of the model.

4 OBSERVATIONS AND CONCLUSIONS

This proceeding paper aimed at demonstrating the general aspects of the centrifuge scope undertaken at Deltares Geo-Centrifuge. Main observations and conclusions from the testing program can be summarized with the following items:

- Although the presently described test only constitutes a singular test within the experimental program, uplift of the cover layer was observed in all tests.
- Uplift phenomena occurs when the limit equilibrium state is satisfied, i.e., the ratio of the vertical pressure exerted by the cover layer is equal to the water pressure below the cover layer, or when $\sigma_v / \sigma_w = 1$.
- The cover layer cracks due to uplift. This crack is seen as a diagonal crack occurring at the toe of the dike, see Figure 7 (to the right of the first white dot in the figure).
- Uplift at a centrifugal acceleration of 80 g causes the cover layer to rise approximately 2.5 mm, see D4 measurements in Figure 6. There have been observations of much severe uplift deformations within the experimental program.
- When g-level increases the vertical displacement of the cover layer reduces. It should be noted that the cover layer remains in an uplifted condition and the ratio σ_v / σ_w remains unaltered when increasing the g-level. The exact cause of this is still under investigation.
- Figure 7 shows that in the uplifted zone the hydraulic head in the sand layer is maximised by the weight of the cover layer. A further increase in hydraulic head at the left boundary will further increase the head at the uplifted zone.
- Failure was found by a combination of a steep sliding plane at the active side that connects the opening at the cover layer with the sand layer.
- In the test series, no passive failure plane is visible, instead the cover layer seems to be horizontally compressed in combination with a further increase in curvature of the uplifted zone. The later could mean that the lateral stiffness of the cover layer might play a role in the observed deformation patterns.

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