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Centrifuge model tests to evaluate the stability of embankments in hydrodynamic conditions

Modélisation en centrifugeuse pour évaluer la stabilité de remblais dans conditions hydrodynamiques

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ABSTRACT: Embankments associated with mine tailings storage facilities, levees, and earth dams have fine granular soils susceptible to liquefaction when their state is on the wet side of the critical state line. During periods of heavy rain or drainage system issues, a partially saturated material can become saturated after infiltration during rainfall. For low degrees of compaction, the response can be contractive, particularly at medium to high confining pressures. Therefore, centrifuge model tests were performed at Deltares, Netherlands, to assess the stability of a slope made of a silty fine sand subjected to seepage flow. An upstream water level was installed inside the slope, allowing a steady-state seepage flow through the model, while water was recovered on the downstream border where the water level was kept at a much lower level. This paper presents the centrifuge test results in terms of pore pressure evolution, which was then compared with numerical analysis performed in PLAXIS 2D®.

RÉSUMÉ: Les remblais associés aux installations de stockage de rejets miniers, aux digues, et aux barrages en terre sont composés de sols granulaires sensibles aux phénomènes de liquéfaction lorsque leur état se situe du côté humide de la ligne d'état critique. Lors des périodes de fortes pluies ou problèmes dans le système de drainage, un matériau partiellement saturé peut le devenir après infiltration. Pour de faibles niveaux de compactage la réponse peut être contractante, en particulier sous contraintes effectives moyennes à élevées. Par conséquent, des essais sur modèles en centrifugeuse ont été réalisés à Deltares, aux Pays-Bas, pour évaluer la stabilité d'une pente constituée d'un sable fin limoneux soumis à un écoulement d'infiltration. Un niveau d'eau est installé à l'intérieur de la pente permettant un débit d'infiltration stable à travers du modèle, tandis que l'eau est récupérée sur la bordure en aval où le niveau d'eau est maintenu à un niveau beaucoup plus bas. L'article présente les résultats des essais en centrifugeuse, notamment l'évolution de la pression interstitielle, qui est comparé aux résultats de l'analyse numérique réalisée dans PLAXIS 2D®.

Keywords: Seepage flow; liquefaction; slope stability; numerical analysis.

1 INTRODUCTION

There are different types of embankments, such as mine tailings storage facilities, levees, and earth dams, facing potential risks under adverse hydrodynamic conditions. These geotechnical structures often contain fine granular soils that can be sensitive to liquefaction when their state is on the wet side of critical state line. If liquefaction is not contained and propagates throughout the deposit, a flow slide results.

For instance, dry stacks are massive embankments of compacted filtered tailings. To construct these massive embankments, the tailings slurry obtained in the mining process passes through a filtering system to reduce its water content. However, the term "dry" stack can be misleading, as the state of the material forming the stack is not entirely dry. Davies (2011) suggests that it is a partially saturated material with a degree of saturation around 70-85%, but this depends on several factors (filtration process, type of material, transportation mode, climate conditions…).

Under inadequate draining conditions, a filtered dry stack in a partially saturated state can become fully saturated through infiltration during rainfall. When the degree of compaction is high (typically over than 95% of standard Proctor), filtered tailings show dilatant response under various confining stresses. Lower degrees of compaction result in a contractive response, particularly under medium to high confining pressures. Additionally, when the material is less compacted and/or on the wet of optimum, it may become saturated under high effective stresses induced by embankment rise. Depending on the material's permeability, mineralogy, and loading rate (due to subsequent lifts), excess pore pressures may develop in the embankment. This can mobilize low undrained strength ratios far from critical state conditions eventually dropping to post-peak residual values, displaying non-Newtonian behaviour (Gens, 2019). In a climate change scenario, the increased frequency of heavy rain and storms poses additional challenges.

For these reasons, design must account for the fact that material strength depends on various factors, including the type of material, degree of saturation and compaction, drainage conditions, effective stresses due to loading, and/or excess pore pressure generation. Driven by the recognition of the brittle nature of liquefaction failure (Morgenstern et al., 2015; Jefferies et al., 2019, Arroyo and Gens, 2021), stress-deformation hydromechanical analyses of tailings dams are replacing the limit equilibrium methods that, until recently, were considered the best available practice for stability analyses (Garbarino et al., 2018, Mánica et al., 2022).

Nevertheless, it is recognised that effective use of these numerical models requires adequate calibration. Without this calibration, any attempt to simulate ground improvement technologies or more stable geometries will be seriously hampered. In a recent European Project, H2020-GEOLAB-SAFETY, simple slope models were tested in a geotechnical centrifuge. This paper presents some of the results obtained, together with hydromechanical numerical analyses.

2 CENTRIFUGE TESTS

The GeoCentrifuge at Deltares is a beam centrifuge with a 260 g-tonne capacity and a platform radius of 5.0 m. The experiment presented here comprises a homogeneous profile of a silty sand obtained with the mixture of two silica based natural soils: 56% of Geba sand and 44% of a fine fraction of Baskarp sand. This mixture allowed the simulation of the grain size distribution curve of an iron tailing material for which dry stacking is being studied. The obtained silty sand has the following physical properties: 47% of fines content, curvature coefficient Cc=0.74, uniformity coefficient Cu=2.94, mean effective diameter D_{50}=0.086 mm, maximum void ratio = 1.03, and minimum void ratio = 0.63. The model is initially prepared with unsaturated loose material by moist tamping (Figure 1), being placed in the centrifuge for an acceleration of 100g. The g-level is applied at the base of the model container corresponding to the base bottom layer of soil. After a permanent steady-state water flow is established, the hydraulic gradient is gradually increased by raising the water head on the left boundary while keeping a low water head at the right boundary. The model is instrumented with 10 pore pressure transducers (PPTs) from MEAS France (EPB-PW-7BS/Z0/PC0.5/L5M) with measuring range between -50 and 700kPa and accuracy of 0.5%FS.

Figure 1. Physical model inside the strongbox.

3 NUMERICAL MODELING

3.1 Geometry and scale factors

Numerical analysis using PLAXIS 2D® simulated the centrifuge experiment at prototype scale. Table 1 summarises the scale factors to convert the physical model results into prototype scale, so that they could be compared to the numerical data. The imposed acceleration was 100 g, although the conversion to the prototype scale used *N* values corresponding to the measured *g* level at each instance. The prototype geometry consists of a 30º slope with a height of 39 m in the upstream boundary and 8 m in the downstream boundary. There's a blanket drain at the bottom right corner of the model, extending 17.2 m from the right boundary (Figure 2).

Table 1. Scaling laws for centrifuge tests at Ng (Taylor, 1995).

Parameter	Scale (Model/Prototype)
Linear dimension (m)	1/N
Stress (kPa)	1
Time for water flow (s)	$1/N^2$

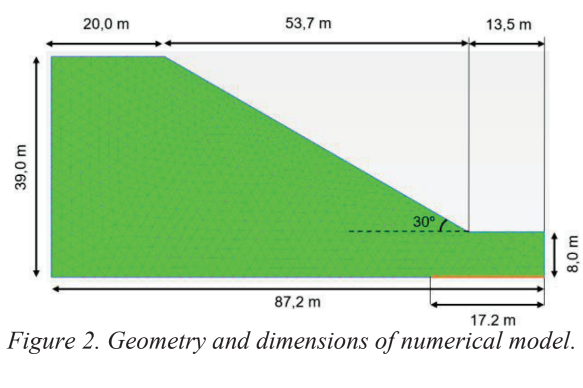

Figure 2. Geometry and dimensions of numerical model.

3.2 Material parameters

The constitutive model used was the linear elastic perfectly plastic Mohr-Coulomb model. The parameters for the material were determined through monotonic compression triaxial tests, conducted in the Geotechnical Laboratory of FEUP. To accurately simulate the unsaturated conditions above the water table, the van Genuchten parameters associated with the soil water retention curve were introduced in the groundwater parameters (Table 2).

Table 2. Soil parameters (Mohr-Coulomb).

Parameter		Value	Unit
Unit weights	γ_{sat}	18.10	kN/m^3
	γ_{unsat}	15.00	kN/m^3
Young Modulus	E	50 000	kPa
Poisson ratio	ν	0.31	-
Friction angle	ϕ'	33.32	º
Initial void ratio	e	0.800	-
Cohesion	c'	0	kPa
Coef. earth pressure at rest	K_0	0.4507	-
Permeability	k_x=k_y	$1x10^{-5}$	m/s
Van Genuchten parameters	S_r	0.00	-
	S_{sat}	1.00	-
	g_n	2.26	-
	g_a	1.82	-
	g_l	-0.66	-

3.3 Mesh and boundary conditions

The PLAXIS® numerical model has plane strain finite elements with triangular 15-node elements. The mesh created for this case is considered "very fine", comprising 13741 nodes in 1680 triangular elements. The bottom boundary was fixed in both directions, while the left and right boundaries were only fixed horizontally.

The numerical analysis comprises two phases: i) an initial phase to activate the stress state (Gravity Loading); ii) a hydromechanical numerical analysis (fully coupled flow-deformation analysis) where the head in the left boundary, and in the drain region were raised gradually, following the head evolutions measured in centrifuge test and shown in Figure 3.

So, the hydraulic boundary conditions during the hydromechanical analysis, comprise a null flux imposed in the bottom boundary, except for the drain region, where a head evolution (head function 1) was applied. In the left boundary, the other head evolution was applied, as indicated in Figure 3 (head function 2). These functions were created to represent the water table conditions observed in the centrifuge test.

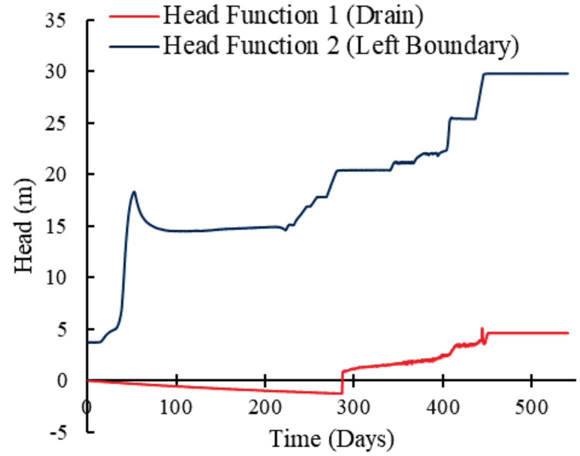

Figure 3. Water table elevation: head evolutions on the left boundary and in the drain region measured in the centrifuge test.

4 RESULTS

The physical and numerical model results are compared in terms of the pore pressures obtained in nine points of the model.

Figure 4 presents the pore pressures at the last phase of the numerical analysis, where a failure happened. The figure also shows the position of the PPTs as well as the position of the water table.

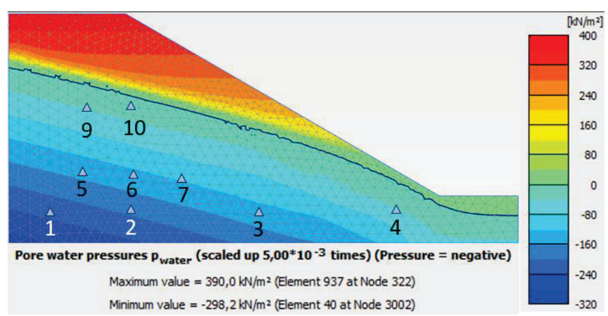

Figure 4. Pore pressure distribution and water table at the last phase of the numerical analysis, as well as the position of selected PPTs.

Figures 5 and 6 show the pore pressure evolution with time in six PPTs. Figure 5 shows that the measured values of the PPTs located close to the left boundary match the calculations well. However, Figure 6 shows that the values differ for the PPTs further away from the left boundary. This indicates that the slope failed faster in the centrifuge test than in the numerical model. This difference may be related to a small erosion at the slope toe that was noticed in the centrifuge test which may have resulted in a faster collapse of the slope than in the calculations.

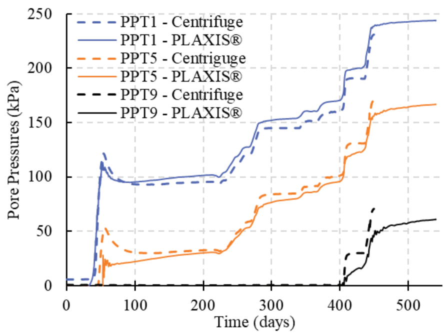

Figure 5. Pore pressures over time (PPTs 1, 5 and 9).

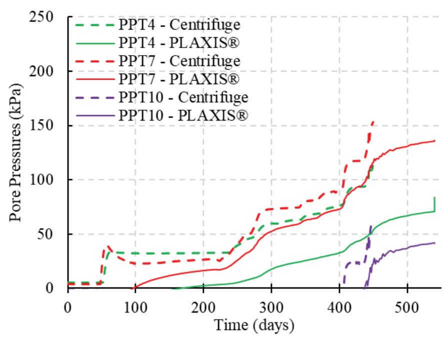

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Figure 6. Pore pressures over time (PPTs 4, 7 and 10).

Indeed, the slope collapses at 540 days in the numerical model and at 450 days in the centrifuge experiment. This is shown by the sharp increase in pore pressure in all considered points at the failure moment. Be aware that the additional 90 days (540-450) corresponds to 13 min in the centrifuge test (model scale). Further studies are being performed on this data, namely to analyse post-mortem results obtained with a mini-CPT and with a laser scan of model surface.

5 CONCLUSIONS

A comparison of the pore pressures registered in the centrifuge test and calculated with the numerical model shows that their values match well for the points closer to the left boundary, showing that the numerical model is well-simulating the water percolation. Furthermore, a similar type of failure was observed in the experiment and the centrifuge test. Slope failure came earlier in the centrifuge test than in the numerical calculations, probably due to the relatively fast erosion of the slope in the centrifuge test. Future developments include the use of advanced numerical analyses capable of simulating soil liquefaction.

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