Numerical study of uplift induced levee failure for the design of a centrifuge test

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Abstract. In geotechnical engineering, physical and numerical models seek to shed light on multiphase phenomena that threaten earth structure stability. This is the case of river levees: when subjected to non-ordinary hydraulic loads, local and global failures with consequent floods could occur. If, on one hand, centrifuge models can replicate the real phenomena, exploiting the enhanced gravity, while scaling geometrical features and time, on the other, numerical models extend the possible case studies by capturing key elements, governing the hydromechanical behaviour of the earthworks. However, the two techniques could complement and benefit each other. In this research, a potential failure mechanism, induced by the development of uplift pressures beneath the toe of a levee characterized by a peculiar stratigraphic profile, is investigated. The foundation consists of a shallow weak low-permeability layer, overlying a coarser and more permeable one, this latter acting as a hydraulic preferential flow path between riverside and landside. Results of a preliminary numerical study carried out with different methods are presented and discussed. The study aims to improve understanding of complex failure mechanisms and to encourage the development of more robust forecasting methods. Indeed the results have provided fundamental guidance for a centrifuge experimental set up.

Keywords: Levee, Geotechnical Centrifuge, Numerical Modelling

1 Introduction

Water retaining geostructures, such as river levees, require continuous development of risk mitigation strategies to cope with the current and prospective increase of hydraulic loads acting on these structures. This study is focused on the geotechnical behaviour of levees, protecting urbanized territories from river flooding. Among several failure modes, those possibly emerging when a levee foundation is characterized by a shallow soft fine-grained layer, overlying a highly permeable sandy layer, are still partially unknown, and thus unpredictable. The coarser layer may be directly interconnected with the river, acting as a hydraulic preferential conduit between riverside and landside. If the water level increases, high overpressure can build up at the interface between the fine-grained and sandy layer, exceeding the overburden stress of the shallow layer on the landside. This circumstance may determine localized toe uplift on the ground level and, simultaneously, favour the progression of a slip surface in the levee body, resulting in a subsequent earth structure collapse, as reported by [1] and [2]. The joint use of centrifuge testing and numerical modelling could be useful to investigate in details these phenomena. In fact, centrifuge modelling is a well-established approach in geotechnics research, still challenging when employed in this context, due to the well-known difficulties to recreate certain stratigraphy and apply time-dependent hydraulic boundary conditions on earth structures. On the other side, the application of various numerical techniques aids in getting a broader picture of the potential instability occurring in the experiment.

This research work seeks to shed light on complex potential failure mechanism that could develop when a preferential flow path establishes in the levee foundation. In particular, predictions determined by different numerical approaches are shown, hence providing guidance in their prospective use in safety assessment practice. It is worth noting that the experiment design of centrifuge tests, besides the numerical outcome, is based on a balanced compromise among physical features of the equipment, time and costs constraints. These aspects will be underlined during the final discussion.

2 Numerical modelling

Three different methods are compared in the safety assessment of the levee: (i) the *Limit Equilibrium Method* (LEM), implemented in the commercial software SLOPE/W [3], which was easily combined with transient seepage analysis performed by SEEP/W, included in the same software suite; (ii) the *Van Method*, available in the D-Stability code [4]; (iii) the *Strength Reduction Routine*, used by PLAXIS 2D [5], which was applied to the results obtained from a coupled seepage-deformation analysis. The numerical modelling was carried out to properly support the design a centrifuge test, however all the simulations have been performed at prototype scale, in keeping with the geometrical similitude between model and prototype [6] expressed by Eq. (1):

$$L_m/L_p = 1/N \tag{1}$$

where N is the scale factor for gravity (i.e. $g_m=N\,g_p$), L_m and L_p are respectively characteristic lengths of model and prototype. The calculation phases in FE model mimic the whole centrifuge test from the acceleration stage, passing through the self-weight equilibrium (during which consolidation occurs), to the flooding stage. Whereas, in SEEP/W and Van Method only the processes occurring after consolidation are reproduced. A parametric study on the thickness of foundation layers is carried out to support the design of the physical model to be tested under an enhanced gravity field and highlight the crucial role of the stratigraphy on the overall stability of the levee.

2.1 Geometry and materials

A plane strain section, designed to be suitable for investigating the potential failure mechanism aforesaid and concurrently easily reproducible as a small-scale physical model, is considered in the numerical study. The prototype levee body is characterized by a height of 7.50 m, a 3.00 m wide crown and slopes inclination of 1H:1V and 1H:1.5V for the riverside and the landside, respectively (Fig. 1). The foundation consists of a fine-grained deposit overlying a layer made of a coarser material, which extends 3 meters beyond the landside toe and is hydraulically connected to the water retained on the riverside. The parametric study consists of a variation of the first subsoil layer thickness of the foundation, between 2.0 m, 2.5 m and 3.0 m, maintaining constant the total foundation height (5.0 m). Hence, the sandy layer changes its thickness accordingly.

The filling material selected for the levee body, typically constituted by a heterogeneous mix of sands and silts, is a compacted mixture of 70% by weight of Ticino Sand (TS) and 30% of Pontida Clay (PON). The optimum moisture content (w = 8.8%) and dry density (γ_d = 20.60 kN/m^3), determined using the Standard Proctor compaction energy, are taken as reference as the initial state of the TS70%-PON30% mixture. For the upper and the bottom layers of the subsoil, which frequently consists of clayey and silty strata deposited in a floodplain environment, a homogeneous consolidated layer of PON and a compacted TS are considered. A pre-overburden vertical effective stress of 800 kPa has been considered for the PON layer; a relative density equal to 80% (γ_d = 15.74 kN/m^3) with a water content of 5.0% has been assumed to define the initial conditions of the TS layer. Soil index and physical main properties are determined for the three materials and can be found in Ventini et al. [7].

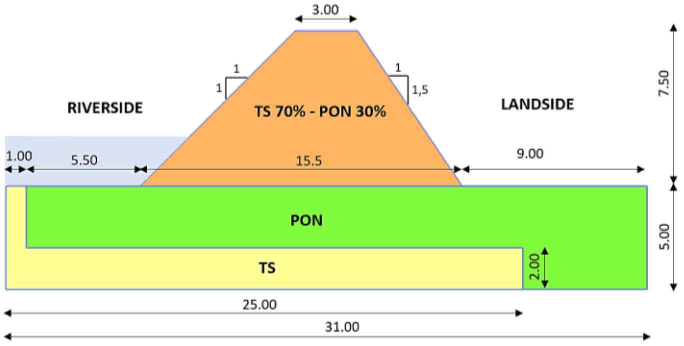

Fig. 1. Geometry of levee section numerically analyzed (in the case of 3.0 m-thick PON layer) in PLAXIS 2D (length unit in m).

2.2 Hydro-mechanical soil properties

The full modelling of the time-dependent hydraulic behaviour is allowed in SEEP/W and PLAXIS 2D, whose results in terms of pore water pressure distributions are respectively used as input of LEM analysis and Strength Reduction method, while D-Stability doesn't account for transient seepage flow. In this last case, total hydraulic heads need to be directly specified for each material and the depicted situation can be considered as a steady-state condition.

Hydraulic and retention properties of the mixture and the clayey silt material, accurately estimated from specific laboratory procedures and extensively discussed in Ventini et al. [7], are listed in Table 1, together with the hydraulic conductivity of the TS, that is considered fully saturated during the entire duration of the analyses. The Mualem-van Genuchten model has been adopted for modelling the soil water retention curves (SWRCs) and hydraulic conductivity functions.

Table 1. Hydraulic and retention parameters used for the seepage analyses in SEEP/W and PLAXIS 2D.

Material	k_{sat} (m/s)	S_{res} (-)	S_{sat} (-)	α_{VG} (kPa)	n_{VG} (1/m)	l (-)
TS70%-PON30%	$1.23 \cdot 10^{-7}$	0.057	1.000	11.9	1.240	-3.347
PON	$6{,}67 \cdot 10^{-10}$	0.000	1.000	142.8	1.455	0.500
TS	$3{,}45 \cdot 10^{-5}$	-	-	-	-	-

For this preliminary application, in SEEP/W, soil porous medium is assumed rigid under partially saturated conditions. Conversely, in PLAXIS 2D, the Hardening Soil (HS) hyperbolic formulation, developed by Duncan and Chang [8] is considered for modelling the mechanical behaviour of the mixture and the sand layer. Whereas, for the fine-grained subsoil layer, the Soft Soil model [9] is used. In all the numerical techniques used in this study, a Mohr-Coulomb failure criterion with drained strength parameters is considered. Soil mechanical properties, derived from standard oedometer tests and triaxial tests are reported in Table 2. Further information on the hydro-mechanical characterization of the three materials can be found in Ventini et al. [7] and Fioravante and Giretti [10].

Table 2. Mechanical and physical parameters assigned to the levee body and foundation units in PLAXIS 2D, according to Hardening Soil and Soft Soil constitutive models.

Material		TS70%-PON30%	PON	TS
Constitutive Model		Hardening Soil	Soft Soil	Hardening Soil
γ_{unsat}	kN/m^3	20.8	18.85	15.74
γ_{sat}	kN/m^3	22.3	21.85	16.53
e_{init}	-	0.30	0.44	0.67
E_{50}^{ref}	kN/m^2	$22.52 \cdot 10^3$	$6.00 \cdot 10^3$	$19.80 \cdot 10^3$
E_{oed}^{ref}	kN/m^2	$10.00 \cdot 10^3$	$4.50 \cdot 10^3$	$14.14 \cdot 10^3$
m	-	0.5	1	0.5
c’	kN/m^2	5.00	2.5	0.0
ϕ’	°	46.00	33	41.00
K_0^{NC}	-	0.287	0.455	0.344
ν	-	0.223	0.20	0.256
λ^*	-	-	0.053	-
κ^*	-	-	0.016	-
M	-	-	1.702	-

2.3 Initial and boundary conditions and testing sequence

The definition of realistic initial conditions in terms of suction and pore water pressure distributions represents a crucial aspect for transient seepage analyses of earthen structures. In PLAXIS 2D, starting from a uniform value of matric suction of about 5 kPa, representative of the physical model preparation state, a constant outflow is assigned to the crest and sides, to reproduce the progressive drying occurring during the centrifuge test. An initial water level, equal to 1.5 m, is supposed to be maintained constant riverside during the in-flight acceleration and consolidation stages, for the time required to attain the equilibrium of pore water pressures (Fig. 2a). The initial conditions after consolidation in PLAXIS 2D are imposed in SEEP/W.

Regarding boundary conditions, since the model is supposed to be contained in a rigid steel box, in the FE analysis, the bottom horizontal, right, and left vertical sides of the subsoil are assumed to be impermeable, with fully and horizontally fixed constraints, respectively. A time-dependent hydrometric condition is imposed on the inner side of the levee. The goal is to identify the critical hydraulic head which would likely trigger a toe uplift mechanism, thus, the effect of five incremental river stages is investigated (Fig. 2b). Each water level is reached with a rate of 0.5 m/days and maintained for a period of 50 days, corresponding to about 30 minutes at the model scale, according to centrifuge scaling laws [6], to guarantee the establishment of a stationary flow regime within the levee body at each step. As mentioned in Sec. 2.1, in D-Stability initial and boundary conditions are not necessary, the water levels are sketched to determine the pore pressure distribution used in the following stability analysis. Two levels are used: a higher one which guarantees high pressures only in TS in agreement with the investigated river stages, while above TS pressures are controlled by the lower water level (see Fig. 5a), to mimic an undrained response of the system with a pressure jump between TS and PON.

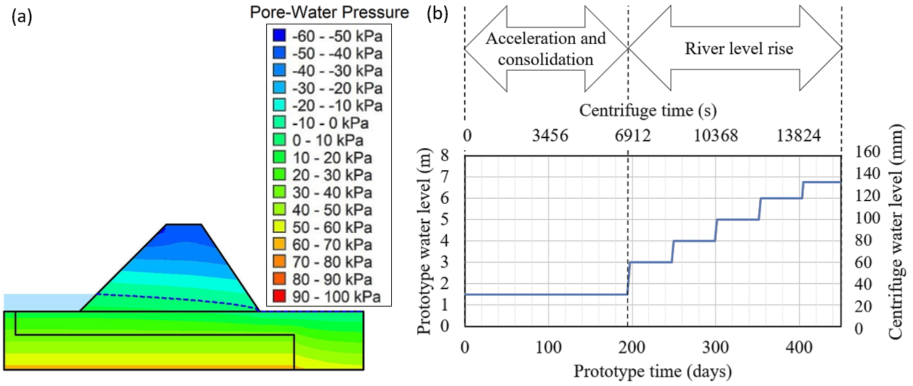

Fig. 2. (a) Initial pore water pressure distribution for transient seepage analyses (isoline increment = 10 kPa), phreatic surface in blue dashed line; (b) Hydraulic head boundary condition assumed in the numerical study, at both prototype and centrifuge scale.

2.4 Results and discussion

Fig. 3 shows FEM numerical results, considering a 3.0 m-thick PON layer with reference to three significant time steps. Following the first water level increment, a sudden increase of pore water pressures occurs in the sand layer. Then, the water level persistence leads to a progressive saturation of the lower part of the levee body and, simultaneously, to a slow rise of pore pressures even in the fine-grained layer. The total deviatoric strains, which appear extremely low at the beginning of the flooding stage and concentrated at the interface between PON and TS, tend to increase, with the advancement of the phreatic surface within the levee and the contextual decrease of vertical effective stresses in the PON layer, highlighting the shape of a possible slip surface. The number of plastic failure points tends to dramatically increase as the hydrometric level rise to 4.0 m, suggesting a significant weakening of the levee section, especially in correspondence of the landside toe, leading to the failure condition.

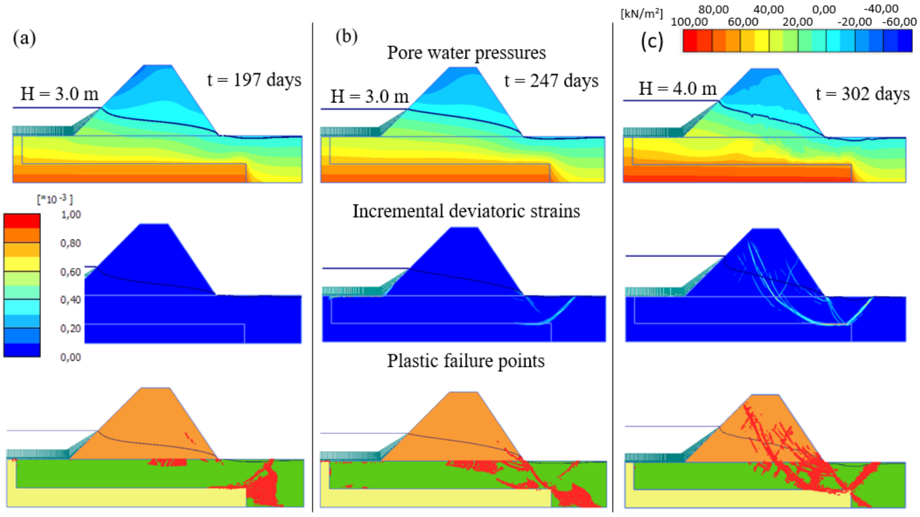

Fig. 3. Pore pressures, total deviatoric strains and plastic failure points at different stages during FEM analysis carried out by means of PLAXIS 2D: (a) at the beginning of the first water level increment (t = 197 days); (b) at the end of the first water level increment (t = 247 days); (c) during the persistence of the critical water level, associated to the failure mechanism (t = 302 days).

The correlation between river stages and their effects in terms of stability is particularly evident observing the evolutions of the Factor of Safety (FS) over time for FEM and LEM in Fig. 4a. For Van Method FS is correlated with the hydraulic head (Fig. 4b). In the FEM and LEM analyses, as soon as the river stage rises to 3.0 m, the increase of pore pressures causes a reduction of shear, resulting in a significant decrease of FS, which tends to further reduce during the persistence of the water level (Fig. 4a). Potential failure conditions, identified by an FS minor than one, are achieved at different time steps and hydrometric loads for the three methods. In particular, in FE analyses, the 2.0 m thick PON layer encounters a critical condition for stability towards the end of the first water level persistence; while for thicknesses 2.5 m and 3.0 m of the PON layer the critical hydraulic heads are higher, respectively 3.8 m and 4.0 m. Indeed, FEM simulations don't converge anymore after these critical water levels are reached, evidencing that outcome is strongly controlled by the limitation of the small-displacements hypothesis. In LEM critical heads are generally higher than those obtained with FEM analyses, thus potential failure occurs for all the geometries but with a certain delay. However, it must be noted that the shape of the slip surface, assumed in these LEM calculations might be not representative of the investigated mechanism. Lastly, in Van Method, FS reduces with the progressive increase of the water level, but only for PON thickness equal to 2.0 m, FS is less than the unit. In the other cases FS>1 probably due to the approximated pore pressure distribution, which results only in high pressure in TS but not in PON. Moreover, the location and shape of the slip surface (Fig. 5b) are similar to those observed in FEM (as visible in the increment of deviatoric strains of Fig. 4). Nonetheless, nothing can be said in terms of deformation for LEM and Van method; hence they are affected by a generally higher level of simplification compared to FEM, which accurately reproduces the coupled flow-deformation behaviour as long as the small displacement hypothesis stands. Overall, with all the three approaches the post-failure behaviour cannot be analyzed, thus it is demanded to the centrifuge test to explore the entire failure event.

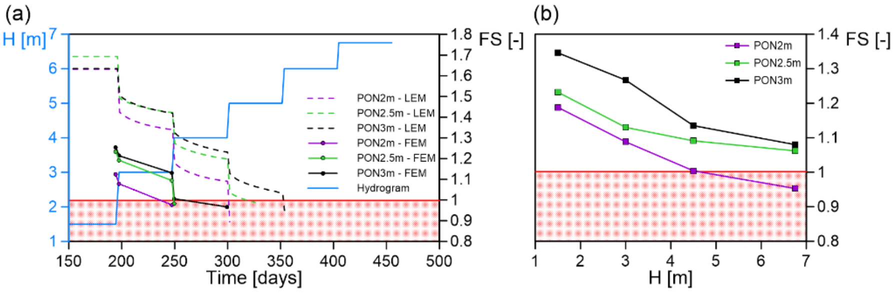

Fig. 4. Variation of FS for the three investigated foundation thicknesses: (a) over time for LEM and FEM analysis; (b) respect to hydraulic heads for Van Method.

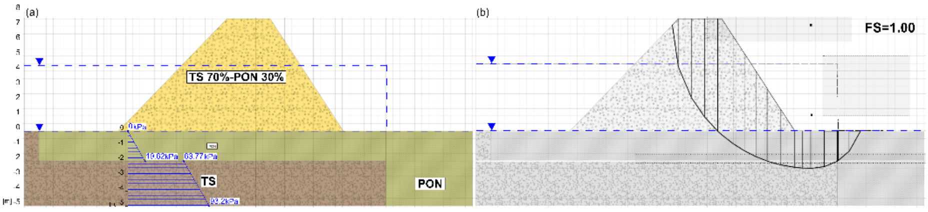

Fig. 5. Piezometric levels and resulting pore pressure distribution for Van Method analysis (a) and Slip surface for FS=1 in the case of PON thickness equal to 2m.

3 Remarks and conclusions

In this work, the results of a numerical study carried out to investigate a river levee failure mechanism induced by toe uplift are presented and discussed. The study provides guidance for the definition of geometrical features of a centrifuge physical model and in particular for the selection of foundation layers thicknesses. Based on FEM and LEM outcomes, the configuration characterized by a PON layer of 3.0 m seems to be the most suitable to replicate the instability of interest and, at the same time, to investigate the effect of a time-dependent boundary condition on the safety performance of the levee. Furthermore, the research confirms that the proposed hydrograph, easily reproducible in the centrifuge apparatus, allows for identifying critical hydraulic heads which may trigger failure. In the light of the simulation outcome, the following monitoring instruments devoted to pick the noteworthy aspects of the phenomena, are recommended: tensiometers in the levee body and on the landside, near the toe; pore pressure transducers in the foundation soils, in both layers; LVDT on the levee crest and near the toe and roto-translative transducers on the landside slope.

4 Acknowledgement

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