INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics

On the hydro-mechanical behavior of an unsaturated river embankment: Centrifuge testing and numerical analysis

E. Dodaro, C.G. Gragnano & G. Gottardi
Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy

R. Ventini, M. Pirone & C. Mancuso
Department of Civil, Building and Environmental Engineering, University of Napoli Federico II, Italy

D. Giretti
Department of Engineering and Applied Science, University of Bergamo, Italy

V. Fioravante
Engineering Department, University of Ferrara, Italy

ABSTRACT: This paper concerns the numerical analysis aimed at reproducing the centrifuge test conducted on a clayey silty sand river embankment, compacted in unsaturated conditions and subjected to a simulated flood event. To investigate the observed behavior during different stages of the test, characterized by incremental acceleration fields, a finite element simulation of the small-scale centrifuge model was developed. An accurate calibration of the hydro-mechanical soil parameters based on a preceding laboratory campaign was used to simulate the centrifuge test. Then, a comparison between the results of numerical simulation and experimental data, collected during centrifuge test, allowed to validate the fully-coupled numerical analysis at the small-scale model and to interpret the hydro-mechanical behavior of the embankment.

Keywords: small-scale numerical modelling, unsaturated soils, fully-coupled analysis, river embankment

1 INTRODUCTION

The enhanced gravitational field imposed during centrifuge tests addresses the fundamental challenge of in-situ stress state replicability, a crucial issue for investigating coupled flow-deformation processes and to take into account the dependency of soil properties on effective confining stress. For these reasons N-g centrifuge testing on dry or fully saturated small-scale models, have been widely performed for integrating the design of earth structures and revealing possible mechanisms of failure. However, only a limited number of tests have actually focused on the response of unsaturated soils, due to the well-known issues related to the monitoring of partially saturated states and to data interpretation. As part of the 'RedReef' research project (acronym of 'Risk Assessment of Earth Dams and River Embankments to Earthquakes and Floods'), a series of centrifuge tests with different hydraulic loading histories imposed on riverside, has been carried out on a clayey silty sand river embankment model, overlying a homogeneous clayey silt foundation layer, representative for riverbank systems of the alpine and Apennines tributaries of river Po. With the aim of investigating the hydro-mechanical response of these earth structures to a simulated flooding, monitoring data from tensiometers, pore water pressure transducers, and LVDTs have been collected during the centrifuge tests. In this paper a numerical interpretation of the first experiment carried out is presented. The purpose is to validate the hydraulic and mechanical soil properties derived from a previous laboratory characterization and to interpret the experimental behavior of embankment at the different incremental acceleration fields. The finite element simulation presented hereafter has been carried out considering physical model dimensions, instead of the full-scale prototype geometry and the different incremental acceleration fields, to realistically reproduce the stress state reached during all the stages of the test. Reliability of the numerical modelling, based on the use of constitutive Hardening Soil Model and Modified Cam-Clay formulation, in predicting pore water pressure changes in the earth structure is also discussed. Further details about centrifuge testing procedure and numerical simulation of the hydraulic response of the river embankment at prototype scale are respectively examined in two companion papers presented at the Conference (i.e., Giretti et al., 2022; Gragnano et al.

2022).

2 CENTRIFUGE TEST

2.1 Case study and materials

With the aim of modelling riverbank system of the main river Po tributaries, which have recently experienced several high-water events, two materials have been selected for model construction. For the embankment, typically constituted by a heterogeneous mix of sands and silts, a compacted mixture of 70% Ticino Sand (TS), and 30% Pontida Clay (PON), has been used, while for the subsoil, which frequently consists of clayey and silty deposits, a homogeneous consolidated layer of Pontida Clay has been selected. For the construction of the embankment the TS70%-PON30% mixture was compacted in four layers under the Standard Proctor energy, at the Optimum moisture content, $w = 8.8\%$ and at a dry density $\gamma_d = 20.6$ kN/m^3, while the base layer has been preliminarily consolidated under the vertical effective stress of 200 kPa. Detailed information on the physical properties of the two materials can be found in Ventini et al. (2021) and Giretti et al. (2022).

2.2 Equipment, model scheme and test procedure

The 240 g-ton geotechnical centrifuge facility available at the Experimental Institute for Geotechnical Modelling (Italian acronym: ISMGEO) of Seriate (Bergamo, Italy), has been used to perform the centrifuge test. The river embankment model (sketched in Figure 1) has been reconstituted in a steel rigid box, having internal dimension of 620 mm x 445 mm x 160 mm and including a transparent frontal side made of Perspex. The embankment, characterized by a simple trapezoidal shape, has been modelled with a height of 150 mm and slopes inclination of 1H:1V and 1H:1.5V for the riverside and the landside, respectively; the foundation consisted of a 100 mm-thick layer.

The middle section of the model was extensively instrumented (see Figure 1) with the purpose of thoroughly investigating the hydro-mechanical behavior of the river embankment model. Eight miniaturized tensiometers, capable of recording both positive and negative pressures (up to 500 kPa of suction) have been placed in the embankment body, at three different depths. Six pore pressure transducers (PPTs) have been embedded in the foundation layer to monitor the pore pressure during the test; one of them (M), was used to control the hydraulic head imposed on the riverside. Two LVDTs (L1 and L3), positioned at the crest of the embankment, have been devoted to the measure of settlements, while two rototranslative transducers (LR2 and LR5) recorded both the horizontal and vertical displacements.

After construction, the model was embarked in centrifuge and subjected to an acceleration field gradually increased in 15 minutes to 50g, which led to the generation of excess pore water pressures in the saturated foundation layer. Then the acceleration has been maintained constant for approximately 2 hours, to attain soil consolidation and the effective stresses equilibrium. Subsequently, water was supplied in the container from an external tank to simulate the river impoundment. Water head has been raised up to about 90% of the embankment height (H), after an intermediate stage at 0.55 H, and kept at this level for about 0.6 hours. Finally, fluid level was progressively lowered. Deeper insights on testing procedure, datasets and monitoring system can be found in Giretti et al. (2022).

3 FINITE ELEMENT MODELLING

A small-scale river embankment model has been numerically reproduced by means of the finite element software PLAXIS 2D (Plaxis, 2021), to analyze the results of a centrifuge test; the adopted soil properties were derived from previous laboratory tests. Particular attention has been paid to the numerical simulation of the consolidation process in the clayey silt layer and to the water pressure changes in the embankment body, due to river level rising.

3.1 Geometry and meshing

The geometry of the plane strain section analyzed, the adopted mesh and the boundary conditions are shown in Figure 1, where the position of the physical model transducers are sketched. Mesh density has been iteratively optimized; in particular a coarseness factor of 0.7 has been selected for the embankment and 0.4 for the foundation layer.

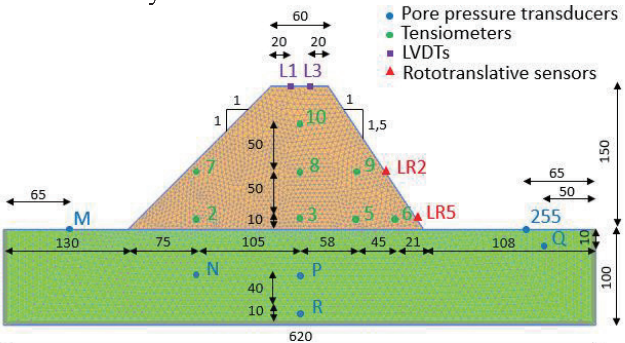

Fig. 1. Geometry of the plane strain section numerically simulated; adopted mesh and position of the instruments (length unit in mm).

3.2 Mechanical and hydraulic properties

The Hardening Soil (HS) model, developed by Duncan and Chang (1970) under the framework of the plasticity theory, has been adopted for modelling the mechanical behavior of the mixture. For the foundation layer the Modified Cam-Clay (MCC) constitutive law, an elastic-plastic strain hardening model, based on Critical State theory and proposed by Muir Wood (1990), has been considered. Soil strength and stiffness parameters derived from standard oedometer and triaxial tests and assumed as input in the finite element analyses are listed in Table 2.

Table 2. Mechanical properties of the embankment and foundation units, according to HS and MCC constitutive models.

Soil		TS70%-PON30%	PON
Model		HS	MCC
γ_{unsat}	kN/m^3	20.8	17.51
γ_{sat}	kN/m^3	22.3	21.01
e_{init}	-	0.30	0.55
E_{50}^{ref}	kN/m^2	$22.52 \cdot 10^3$	-
E_{oed}^{ref}	kN/m^2	$10.00 \cdot 10^3$	-
E_{ur}^{ref}	kN/m^2	$67.56 \cdot 10^3$	-
m	-	0.5	-
c’	kN/m^2	5.00	-
ϕ’	°	46.00	-
K_0^{NC}	-	0.287	0.596
ν	-	0.223	0.20
λ	-	-	0.074
κ	-	-	0.055
M	-	-	1.33

Hydraulic and retention properties of the mixture and the clayey silt material (shown in Table 3) have been accurately evaluated from constant head permeability tests, evaporation tests and psychrometric measurements, except for the saturated permeability of the PON, which has been indirectly evaluated from two oedometer tests. The non-hysterectical Mualem-van Genuchten model (1980) has been adopted for the fitting of experimental data, through the parameters g_n, g_a, g_l. Further information on the hydro-mechanical characterization of the two materials can be found in Ventini et al. (2021).

Table 3. Hydraulic and retention parameter considered for the consolidation and coupled flow-deformation analysis.

Unit	k_{sat} (m/s)	S_{res} (-)	S_{sat} (-)	g_n (-)	g_a (1/m)	g_l (-)
Embankment	$1.23 \cdot 10^{-7}$	0.057	1.000	1.240	0.821	-3.350
Foundation	$6{,}67 \cdot 10^{-10}$	0.000	1.000	1.455	0.070	-0.584

3.3 Calculation phases

The effective stress state of the model at 1-g followed by the actual accelerated field have been reproduced. The peculiar conditions imposed by the centrifugal environment, such as stress and hydraulic head histories, constraints and gravity fields, have been properly accounted for in numerical analyses. To reproduce the reconstruction stages of the model at 1-g, in the initial phase of the simulation, only the foundation layer has been activated and a pre-overburden pressure (POP) distribution, starting from 200 kPa at the ground level and linearly variable with depth, has been imposed to generate the preconsolidation stress of the soil strata. Vertical and horizontal effective stress-fields have been initialized with the *K0 procedure*. Afterwards, the embankment construction has been reproduced by means of an elastic-plastic deformation analysis (*plastic analysis*) in which the foundation is modelled as undrained material, thus, excess pore water pressures have been calculated. In-flight post construction stages, characterized by the gradual increase of the angular speed of centrifuge, have been simulated through consolidation analyses, by considering an appropriate average weight multiplier factor (*ΣMweight*) uniformly applied on the whole numerical model (as a working hypothesis the distortion of the centrifugal field was neglected). The dissipation of excess pore water pressures, developed in the foundation layer after the enhancement of the gravitational field, has been simulated by means of further consolidation stages, applied along the same time as that used in the centrifuge test, as showed in Fig. 2. Finally, a coupled flow-deformation analysis has been carried out to investigate the transient groundwater seepage flow due to the rising of the water level.

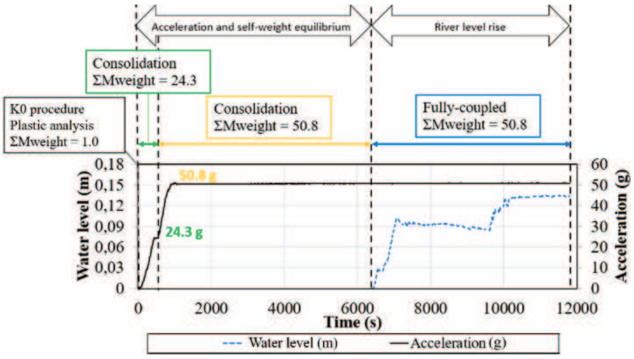

Fig. 2. Time history of the acceleration applied during the stages of the test, hydrograph and calculation phases.

3.4 Initial and boundary conditions

A condition representative for the model preparation state consisting in a constant value of matric suction of about 5 kPa in the embankment body and the water table at the ground level, has been assumed in the initial phase of the analysis. As mentioned, since the model is contained in a rigid steel box, the bottom horizontal, right, and left vertical sides of the foundation layer were assumed to be fully and horizontally fixed, respectively, and impermeable. Three interfaces, characterized by the Young’s modulus of the steel and a permeability of 10^{-5} m/s, have been also included in the model, to take into account possible flow channels between the foundation unit and the container walls. A zero head boundary conditions have been assigned to the top surface of the foundation on the landside to simulate a water outlet zone. A variable hydrometric condition, derived from PPT M measurements, has been imposed during a coupled flow-deformation analysis to reproduce river level fluctuations, on the riverside surfaces potentially affected by water action. The unrealistic hydrometric peak persistence, applied during the flooding stage, has been purposely maintained to achieve a steady state seepage condition, in equilibrium with the relevant hydraulic load of 0.9 H.

3.5 Validation of the hydro-mechanical numerical modelling

Pore pressures data recorded from the PPTs N, P and R during the model acceleration stages and the subsequent consolidation process, are plotted in Figure 3, overlaid to the numerical results obtained from the observational nodes. The trend of the curves suggests a general good agreement between analyses results and experimental data, confirming the reliability of the soil parameters assumed as input of the analyses, although some slight differences in the equilibrium pore pressure values can be detected from the plot, especially for the node R. This is likely due to the capability of the numerical model to dissipate the excess pore water pressures more quickly than the physical clayey silt unit.

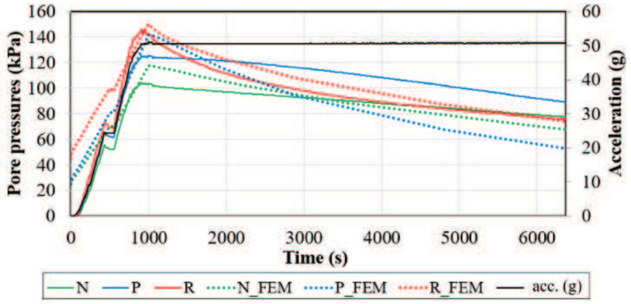

Fig. 3. Pore pressures recorded from PPTs N, P, R and calculated in the corresponding observation nodes from the numerical analyses, during the acceleration and consolidation stages.

Figure 4 shows the comparison between experimental data recorded from the tensiometers embedded in the embankment body of the model and the corresponding stress points in the numerical simulations during the flooding stage. The calculated pore pressure values are very similar to the recorded ones, except data series from tensiometers 10, which suggests a greater tendency of the physical crest to desiccate.

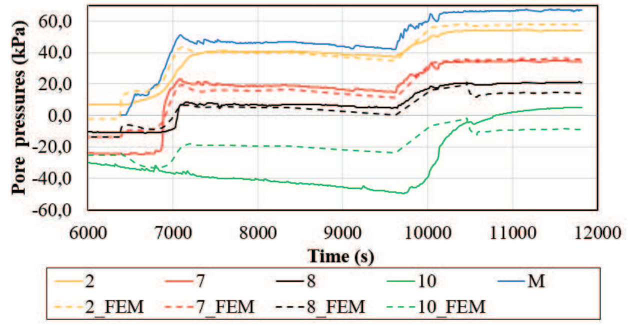

Fig. 4. Pore pressures measured by the tensiometers 2, 7, 8, 10, during the flooding stage, and calculated in the corresponding observation nodes in the FEM numerical simulation.

The trend of settlements of the embankment vs. time observed during the acceleration and consolidation stages recorded by the LVDTs and rototranslative sensors is reported in Figure 5, together with the corresponding numerical results. It is noticeable that the greater part of the vertical total displacement (equal to 7.4mm) occurs when the angular speed of the centrifuge is increased. The displacements are also clearly reproduced by numerical simulation, in which settlements of 6.3mm and 4.70mm are obtained at the crest of the embankment and at height of 60 mm on the landside, respectively.

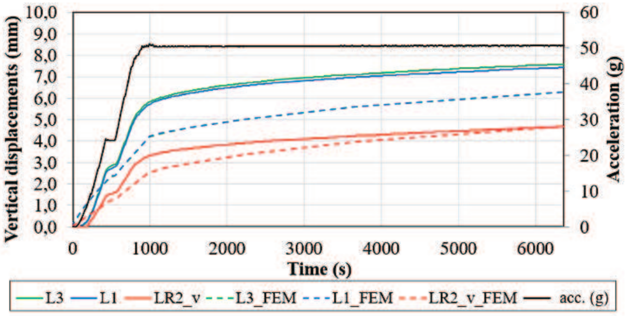

Fig. 5. Vertical displacement recorded from LVDTs L1, L3 and rototranslative sensor LR2 and corresponding numerical results, during the acceleration and self-weight equilibrium stages.

4 CONCLUSIONS

In this paper, a finite element simulation of a centrifuge test carried out on a river embankment model, at the small physical scale, has been presented, with the aim of investigating the hydro-mechanical response of the earth structure, as consequence of a simulated flooding. The comparison between experimental results and numerical simulation shows a very good agreement, validating the hydro-mechanical characterization adopted and the capability of accurate FEM modelling to reproduce the behaviour of complex soil structures.

AKNOWNLEDGMENT

This research was funded under the scheme for "Research Projects of National Relevance" (in Italian: Progetti di Ricerca di Rilevante Interesse Nazionale - PRIN), Bando 2017, grant number 2017YPMBWJ, promoted by the Italian Ministry of Education, University and Research (in Italian: Ministero dell'Istruzione, dell'Università e della Ricerca—MIUR).

REFERENCES

Duncan, J.M., Chang, C.Y. 1970. Nonlinear analysis of stress and strain in soil. Journal of the Soil Mechanics and Foundation, 96: 1629–1653.

Giretti, D., Pirone, M., Dodaro, E., Ventini, R., Gragnano, C.G., Fioravante, V., Mancuso, C., Gottardi, G., Gabrieli, F. 2022. Centrifuge modelling of a river embankment subjected to transient seepage conditions. *Proc. intern. conf. ICPMG Daejeon, 19-23 September 2022.*

Gragnano C.G., Pirone M., Giretti D., Dodaro, E., Ventini R., Fioravante, V., Mancuso, C., Gottardi, G. 2022. Numerical investigations of a transient seepage process in the design and validation of a river embankment centrifuge test. *ICPMG; Proc. intern. conf., Daejeon, 19-23 September 2022.*

Muir Wood, D. 1990. *Soil Behaviour and Critical State Soil Mechanics*. Cambridge: Cambridge University Press.

Plaxis, 2020. *Reference manual*. Bentley Systems Incorporated: Delft, The Netherlands.

Ventini R., Dodaro, E., Gragnano C.G., Giretti D., Pirone M. 2021. Experimental and numerical investigations of a river embankment model under transient seepage conditions. *Geosciences* 11, 192.