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
© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5

Numerical investigations of a transient seepage process in the design and validation of a river embankment centrifuge test

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

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

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

V. Fioravante
Engineering Department, University of Ferrara, Italy

ABSTRACT: In the present contribution, a seepage induced in an earth river embankment is investigated by numerical simulations, using soil characterization derived from an experimental laboratory investigation and varying the boundary conditions to the embankment according to a centrifuge test. A validation of the scaling laws of the processes involving water flow through an unsaturated soil has been attempted by comparing numerical analysis results and experimental data observed in selected points where data from the centrifuge test were available.

Keywords: prototype results, full-scale problem, partial saturation, river embankment

1 INTRODUCTION

Centrifuge test represents a compound and complex experimental tool that has been used for decades in various fields of geotechnical research. The perspective offered by scaling laws (Garnier et al., 2007), due to the application of an increased field of acceleration, allows physical models to be representative for large scale problems; moreover, a wide series of physical processes may be simulated in relatively short times and highly controlled environments (e.g., consolidation in fine grained soils, transient seepage through earth embankment). Nevertheless, in the design of a centrifuge model, a series of uncertainties may affect the blind prediction of the test and its implementation in the design process, which are generally related to soil behaviour in representative fields of stress. Furthermore, the theoretical scaling laws could slightly differ from the actual ones. This is particularly relevant in the analysis of transient processes, where time is also a scalable variable. These aspects may affect the presumed equivalence among physical model and prototype; therefore, convenient strategies are required to improve the representativeness of the test results. In this sense, the use of a thoughtful monitoring system and the chance of considering an increasing complexity in the experimental setups allow to accomplish the targets of an optimal design and a proper validation of the models. Aware of this, in the research project "Risk Assessment of Earth Dams and River Embankments to Earthquakes and Floods", some earth structures subjected to flood waves have been studied, starting with a centrifuge test with a simplified hydraulic loading history. In this paper, results from numerical analysis will be presented in comparison with the data collected during the centrifuge test with the aim to validate the design assumptions about the material behaviour (in terms of soil parameters and scaling laws) under an increased gravity field. Due to the breadth of topics, the paper focuses exclusively on describing the embankment response at the prototype scale in comparison with data monitored. Further information on the centrifuge test execution and the numerical analysis performed at the model scale are discussed in companion papers presented at the Conference (Dodaro et al., 2022; Giretti et al., 2022).

2 EXPERIMENTAL ACTIVITIES

2.1 Materials and properties

The small-scale model is made of two soil layers, in reference to usual field conditions. The filling material of the embankment is here constituted by a compacted mixture of Ticino sand (70%) and Pontida clay (30%), resulting in a clayey, silty sand according to the USCS, characterized by a mean particle size (D_{50}) equal to 0.458 mm and uniformity coefficient (U_c) equal to 246.1. The material properties have been determined under different compaction conditions from an experimental laboratory investigation; for the initial state in physical model preparation, values of γ_d = 20.6 kN/m^3 and w = 8.8% have been considered, obtained under standard Proctor energy, typical for earthen retaining structures. The embankment foundation is made of a homogeneous layer of Pontida clay, which is a kaolinitic clayey silt, with a D_{50} = 0.015 mm and a Plasticity Index (*PI*) of about 10.5%; this unit has been consolidated under the vertical effective stress of 200 kPa. Additional details on the hydro-mechanical laboratory characterization of the two soils can be found in Ventini et al. (2021).

2.2 The physical model setup

The physical model has been designed to be a schematic representation of a water retaining structure (e.g. riverbanks, earth-fill dam) with a trapezoidal shape having a height of 150 mm overlying a foundation layer with a height of 100 mm. All have been contained in a metal box with dimensions 620 mm (parallel to the axis of rotation), 160 mm (perpendicular to the axis of rotation) and a height of 445 mm, with a frontal side made of transparent Perspex. The embankment has been modelled with slopes of 1:1 towards the water side and 1.5:1 towards the dry side. The test has been performed in the 240 g-ton geotechnical centrifuge facility at the Experimental Institute for Geotechnical Modelling (ISMGEO) of Seriate (Bergamo, Italy). With a total arm (i.e. distance among the center of rotation and the base of the model) of about 2.15m, the centrifuge acceleration target has been set at 50g, stabilized in about 1000 seconds from the start of the test, with a slight variation of the acceleration field along the embankment height.

The centrifuge test has been performed through three stages: firstly, the model was accelerated up to the target; the load has been kept constant as long as the equilibrium in stresses has been reached and consolidation in the clay layer was mostly achieved (for about 1.75h). During this stage, water has not been supplied to the container. Then, hydraulic head has been imposed at the riverside slope (1:1); initially, the retained water level has been kept equal to about 55% of the embankment height for about 0.9h, after that it was raised up to ≈ 90% of the embankment height for an additional 0.6h. Finally, the hydraulic head was gradually reduced until it has been possible to stop the test. The whole procedure has an overall duration of about 4.5h. More information on the test execution are presented in Giretti et al. (2022).

2.3 The monitoring system

The use of a monitoring system has been crucial to determine and understand the hydro-mechanical behavior of the small-scale embankment. In the foundation layer, six pore pressure transducers have been placed: three beneath the embankment (to monitor the consolidation process in the clay unit and the pore pressure variations induced by the flood), one on the riverside (to monitor the effective hydraulic head in the model) and two on the land side (to monitor the outflow). In the embankment, eight miniaturised tensiometers have been installed at three different depths from the crown, variously placed from the river to the land side. At the embankment top, two LVDTs are used to monitor vertical displacements, while two rototranslative transducers have been positioned on the land side slope. All sensors have been installed in the middle section of the model, to reduce the influence of side effects.

3 NUMERICAL MODELLING

In the present contribution, the main focus is devoted to the comparison among monitoring data, measured during the flooding stage of the centrifuge test, and numerical results, carried out at the prototype scale using theoretical scaling laws and soil properties determined from the laboratory tests. The general description of all dataset, the analysis of the consolidation process and the numerical model at the small-scale are out of the scope of the paper and are discussed in detail in the companion papers (Dodaro et al., 2022; Giretti et al., 2022).

3.1 Seepage modelling and governing equations

The 2D Finite Element analysis performed by means of the code SEEP/W (Geo-slope, 2018) has been adopted in the present work. Both steady-state and transient conditions have been considered to determine the impact of flooding on pore pressure distributions in the model. The governing partial differential equation are expressed in the form of the Richard's mass conservation law, as:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)+Q=\frac{\partial \theta}{\partial t} \tag{1}$$

where h = total hydraulic head; $k_x = k_z$ = soil permeability in x and z directions; Q = applied boundary flux of water; θ = volumetric water content and t = time. Soil hydraulic conductivity variation with the matric suction has been derived from the soil water retention curves, considering the model proposed by Mualem (1976), equation 2, with function parameters suggested by van Genuchten (1980), equation 3, according to:

$$k = k_{sat}k_r = k_{sat}{S_e}^l\left[1-\left(1-{S_e}^{\frac{1}{m_{VG}}}\right)^{m_{VG}}\right]^2 \tag{2}$$

$$S_e = \left\{\frac{1}{1+[(s)/\alpha_{VG}]^{n_{VG}}}\right\}^{1-\frac{1}{n_{VG}}} \tag{3}$$

where the relative permeability (k_r) is determined from the effective degree of saturation (S_e), with this latter expressed as a function of the matric suction (s), whereas α_{VG}, n_{VG}, m_{VG} = 1-1/n_{VG} and l are model parameters. An automatically adaptive time stepping has been considered for transient analyses.

3.2 The prototype geometry

The geometry considered for the analysis has been obtained using the following assumptions: the physical model dimensions have been linearly scaled considering an average value of the centrifuge acceleration estimated at the base of the embankment during the flooding stage ($n \approx 47.0$ g). The deformation pattern at the end of the consolidation stage has been considered to stretch the model geometry. Through this latter procedure, the slopes of the embankment are slightly lower respect to the configuration initially prepared, due to the lateral spread caused by consolidation settlements occurred in the foundation layer. In Figure 1 the prototype model pointing out the observation nodes considered for the comparison among numerical and experimental data, corresponding to sensors installed in the physical model, is so drawn. The calculation mesh is mainly made of quadrilateral elements with 0.3m as approximate global element size, consisting in a total of 4914 nodes and 4821 elements. About the hydraulic properties, all the parameters of Mualem-van Genuchten model (1980) are determined from the best fitting of the equations 1-2 to laboratory test results (e.g. Ventini et al., 2021). Model parameters for the two soil units are listed in Table 1.

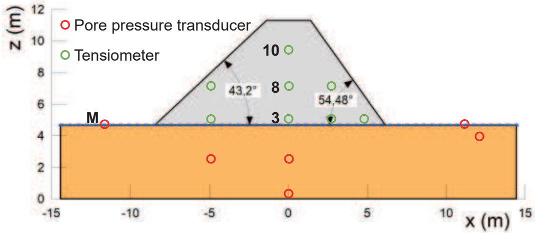

Fig. 1. Model geometry at the prototype scale, with the observation nodes considered for comparison to data monitoring.

Table 1. Soil hydraulic parameters used in the seepage analysis.

Unit	α_{VG} (kPa)	n_{VG} (-)	k_{sat} (m/s)	1 (-)
Embankment	11.9	1.240	1.23E-07	-3.347
Foundation	142.8	1.455	6.67E-10	0.500

3.3 Initial and boundary conditions

For the present study, monitoring data collected during the consolidation in the centrifuge test are used to determine the distribution of pore pressure to be assigned to the numerical model at the initial step of flooding. In particular, the consolidation phase carried out in the centrifuge has been modelled by applying a constant outflow to the embankment surface starting from a constant value of matric suction in the embankment of about 5 kPa (representative of the initial state in physical model preparation state). The aim is to match the changes in pore pressures measured by the sensors in the centrifuge model. Furthermore, a zero head boundary conditions have been assigned to the top surface of the foundation, while impermeable boundaries have been defined to its bottom and lateral areas, in order to simulate the presence of the centrifuge container. Through this procedure, the distribution of pore pressure and suction, to be applied prior to the flooding event, has been obtained in the embankment. Measures from the tensiometers 3-8-10 (installed in the physical model, PM) and data from the correspondent observation nodes in the numerical (FEM) analysis during consolidation are plotted in Figure 2 and show a satisfactory comparison, particularly referring to the pore pressure values in the final calculation steps; the time variable is expressed both in seconds or days, depending on whether referred to the centrifuge test or prototype. Then, for the simulation of the flooding event, the use of a pressure transducer on the ground level on the river side (M) has allowed to measure the hydrometric fluctuations, as subsequently plotted in Figure 3. These data have been considered as the boundary conditions in terms of total hydraulic head during the flooding stage. It has been always assumed a scaling laws for the time equal to n^2 in the numerical analysis at the prototype scale.

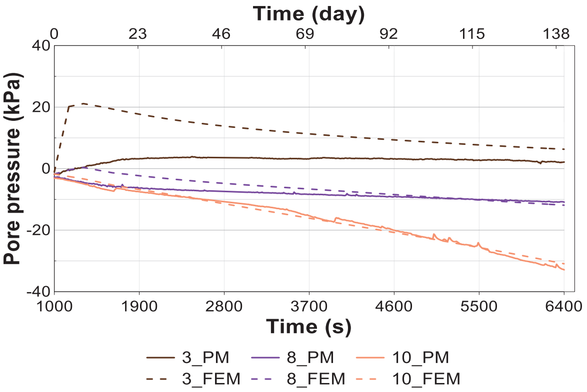

Fig. 2. Pore pressures measured in tensiometers 3, 8 and 10 of the physical model (PM) and calculated in observation nodes in the numerical (FEM) analysis during the consolidation stage.

4 RESULTS OF NUMERICAL MODELLING

4.1 Model validation

Data from physical model (PM) and numerical analysis (FEM) are both plotted in Figure 3; these may summarily represent the hydraulic response of the embankment subjected to variously persistent hydrometric levels, as registered from the pressure transducer M. A generally good match can be observed from this comparison, globally strengthening the validity of the scaling laws on model geometry, time and soil parameters carried out so far. More specifically, the equilibrium pore pressure values at the lower depths (tens.8, tens.10) are similar among PM and FEM, even though the monitoring data appears slightly more responsive to hydrometric variations respect to numerical results. On the contrary, data series from tensiometer 3, at the bottom of the embankment, seems to be quite flat, while the numerical results appear much more sensitive to the external hydraulic load. However, it can be presumed that this sensor has not provided representative data for the hydraulic response of the filling material, being installed close to the interface with the foundation layer and eventually including in its monitoring volume also the clay unit.

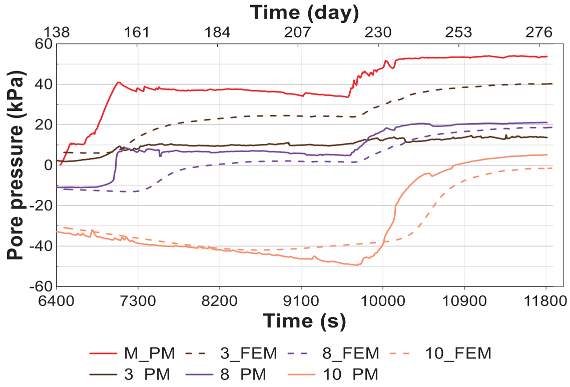

Fig. 3. Pore pressures measured in tensiometers 3, 8 and 10 of the physical model (PM) and calculated in observation nodes in the numerical (FEM) analysis during the flooding stage.

4.2 Stability issues

The duration of the flood event here considered, extremely long, is certainly unrepresentative of a realistic river flooding event and has been purposely considered in order to achieve a steady state seepage condition in equilibrium with a relevant hydraulic load often assumed in riverbank safety assessment for design and verification purposes. Despite this, there has been no significant evidence of any overall instability phenomenon. This outcome has been mainly ascribed to the remarkable shear resistance of the embankment soil, even after the progressive saturation of the embankment, when the suction contribution to strength has been reduced. In fact, the peak strength parameters for the Mohr-Coulomb envelope are a friction angle of 45.5° and an effective cohesion of 5 kPa (Ventini et al., 2021). Therefore, as also evidenced by back-calculation performed with the Limit Equilibrium Method (Geo-slope, 2017), under steady state conditions associated with the maximum water level experienced on riverside slope during the centrifuge test, the minimum value of the Factor of Safety resulted > 1 (see Fig. 4).

5 FINAL REMARKS AND CONCLUSION

In the present contribution, numerical analysis of a physical model at the prototype has been presented to achieve a clear understanding of the hydraulic behavior of an earth embankment tested in a centrifuge test. Different water levels have been considered, with significant persistency, in order to determine the validity on some crucial assumptions made on model properties. The good comparison among FEM and PM data allows the validation of the scaling laws involved in the flow process and gives the possibility to rely on a trustful tool, i.e. the seepage modelling, for the design of further experimental test and the interpretation of monitoring data. However, little can be actually said on the riverbank failure prediction, being the stability conditions always sufficient to ensure overall equilibrium. In this regard, both from numerical analysis and experimental test, it clearly appears here that the persistence of a high retained water alone level can hardly produce a slope instability, while the concurrence of other criticisms (e.g. local weakness of the embankment section, uplift and/or overtopping occurrences) may lastly trigger the riverbank failure.

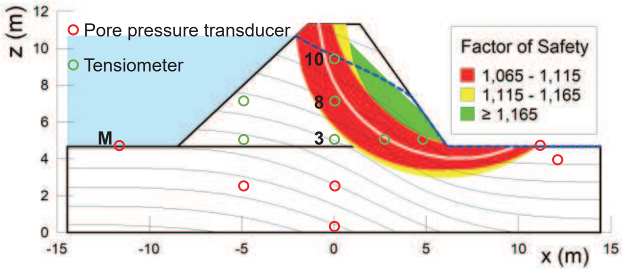

Fig. 4. Results of stability LEM analysis in steady state conditions, with the maximum hydrometric peak recorded in the flood event.

ACKNOWLEDGEMENT

This work has been supported by the project "REDREEF - Risk Assessment of Earth Dams and River Embankment to Earthquakes and Floods" – grant 2017YPMBWJ, funded by the Italian Ministry of Education, University and Research (Progetti di Ricerca di Rilevante Interesse Nazionale – PRIN – Bando 2017).

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