Physical Modelling in Geotechnics

Centrifuge modelling of a river embankment subjected to transient seepage conditions

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

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

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

V. Fioravante
Engineering Department, University of Ferrara, Italy

F. Gabrieli
Department of Civil, Environmental and Architectural Engineering, University of Padova, Italy

ABSTRACT: This paper reports the results of a centrifuge test on a silty sand river embankment compacted in unsaturated conditions and subjected to flooding. The measures of pore water pressure from tensiometers and pore pressure transducers show that the saturation line reaches the landside only after an unrealistic long-lasting flood, proving that the assumption of steady-state seepage for the design or assessment of a river embankment is too much conservative approach.

Keywords: model embankment, partial saturation, transient seepage

1 INTRODUCTION

Safety conditions and preservation of earthworks used for hydraulic regimentation is a priority in land use management, considering their key role for territories safeguard. While the vulnerability of new structures is controlled by proper design and construction methodologies, many existing levees do not satisfy modern design criteria and were built according to empirical rules. For instance, the assessment of hydraulic and mechanical behaviour of river embankments are frequently performed under the simplified hypothesis of steady-state seepage by neglecting the unsaturated soil behaviour. In fact, due to the transient hydraulic loads acting at upper boundary as rainfall and evapotranspiration, soil water content and pore water pressure vary with time strongly influencing the bank stability conditions.

Improvement of predictive capabilities of safety conditions of existing earth structures may be pursued through the interpretation of data obtained from monitoring activities and proper calibration of predictive tools. In this context, physical modelling of earth structures under transient seepage may provide valuable data for the calibration of numerical predictive tools. To this aim, this paper briefly presents the results of a centrifuge test on a silty sand model river embankment compacted in unsaturated conditions and subjected to simulated flooding. The embankment was founded on a fully saturated clayey silt layer. Both the foundation and the embankment were instrumented with pore pressure transducers and tensiometers to monitor the variation of pore pressure and matric suction during the progressive increasing of the river level and consequent saturation of the bank. An insight into the evolution of hydraulic regime established in the model during the test is carried out by analysing the suction and pore water pressure measurements.

Two companion contributions presented at the Conference (Gragnano et al. 2022; Dodaro et al. 2022), discuss respectively the issue of scaling laws in transient seepage processes and the application of the fully-coupled hydro-mechanical numerical modelling to the experimental results here presented.

2 CENTRIFUGE MODEL AND MATERIALS

The test has been carried out using the 6 m diameter geotechnical centrifuge at the ISMGEO laboratory (Italy). The model was reconstituted within a prismatic container, whose internal dimensions are: length = 620 mm, height = 445 mm, width = 160 mm, and whose lateral wall is made of transparent Perspex. A geometrical scaling factor N = 50 was adopted and the acceleration a = 50g was applied at the container base. Figure 1 shows a scheme of the model embankment, which was 150 mm high (7.5 at the prototype scale) and 45° and 56° sloped riverside and landside, respectively. The soil embankment was reconstituted using a mixture of 70% by dry weight of Ticino Sand (TS4), (Fioravante and Giretti, 2016) and 30% of Pontida Clay (PON), (Ventini et al. 2021, Hueckel et al., 1990, 1991). The grain size distribution of the mixture is shown in Figure 2, compared to the PSD of TS4 and PON. The mixture was compacted in four strata at the optimum water content and dry unit weight of the Proctor Standard test. The embankment was founded on a 100 mm deep layer of PON (5 m at the prototype scale), vertically consolidated from a slurry at a vertical stress of 200 kPa. The hydro-mechanical characteristics of the mixture are discussed in Ventini et al. 2021; Table 1 lists the main physical properties of the experimental materials; Table 2 summarises the test conditions of the bank and the foundation layer.

As shown in Figure 1, the model embankment was instrumented with eight miniaturised tensiometers capable of measuring suctions up to 500 kPa and suitable for measuring both positive and negative pressures. Two linear displacement transducers (L1 and L3) monitored the vertical settlement of the crest; two rototranslative sensors (LR2 and LR5) measured the landside slope displacements. Four pore pressure transducers were embedded in the foundation layer; two further PPTs measured the water level riverside (M) and landside (255). Target markers were embedded in the lateral section of the embankment exposed by the transparent window for digital imaging. A picture of the model at the end of the in-flight consolidation is displayed in Figure 3.

Once reconstituted, the model was accelerated to the target angular velocity and allowed to reach the self-weight equilibrium for about two hours. Then, the river level was raised. The fluid used for the test was water, mixed with a white pigment to be more visible. The fluid stored in a tank external to the centrifuge and connected to the model via a pipe, was allowed to flow within the centrifuge basket through a hole drilled in its wall at the level of the toe of the embankment. The flow was controlled by a valve and the fluid level was monitored by PPT M (Fig. 1). Once a given level was reached, the valve was closed and the impounding level was further regulated using a wedge hydraulically actioned. The wedge is highlighted in Figure 3. The test consisted of the following phases: acceleration (from time 0 to time t_1), equilibrium (from t_1 to t_2), river level raising (from t_2 to t_4) and lowering (after t_4) (see -x- axis of Fig. 4).

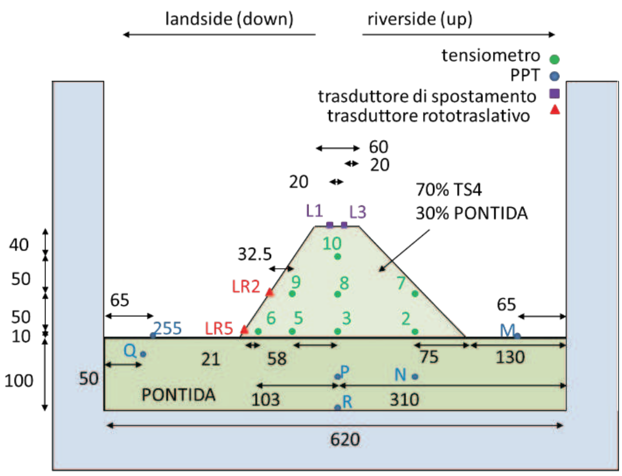

Fig. 1. Scheme of the model embankment (length unit in mm).

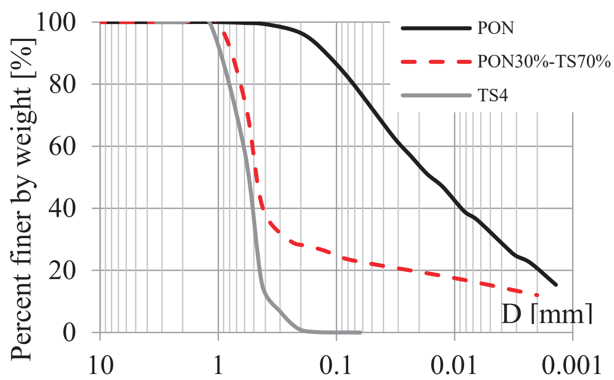

Fig. 2. Grain size distribution of the testing soils.

Table 1. Physical and mechanical properties of the testing soils.

Soil		TS4	PON	TS70%-PON30%
γ_{min}	kN/m³	13.64	-	13.48
γ_{max}	kN/m³	16.67	-	21.3
e_{min}	-	0.574	-	0.236
e_{max}	-	0.923	-	0.953
G_s	-	2.671	2.744	2.684
D_{50}	mm	0.574	0.015	0.458
U_c	-	1.83	-	246.06
LL	%	-	23.61	17.66
PL	%	-	13.13	10.23
PI	%	-	10.48	7.42
ϕ'_{cv}	°	34	33	34

Table 2. Testing conditions.

	Soil	PON	TS70%-PON30%
γ_d	kN/m³	17	20.6
γ	kN/m³	20.6	22.4
w	%	21	8.8
suction	kPa	-	4.9
k_{sat}	m/s	6.67E-10	1.23E-07

3 TEST RESULTS

Figure 4 reports the time history of pore water pressure (PWP), measured during the whole test by the sensors located along the central axis of the embankment; the measures by PPT M are also shown. Time is represented at both the model and the prototype scale. In Figure 5 the vertical displacements of the embankment top and landside slope are plotted at the model scale.

The first test stage consisted in the centrifuge rotation and model consolidation. Positive pore water pressure was generated in the fine-grained foundation layer (see PPT P and R in Fig. 4) during the spin-up, then, once the target acceleration was reached, PWP started to decrease toward the equilibrium (hydrostatic value). With regards to the embankment soil, all the tensiometers registered an initial suction of about 5 kPa; in the upper part of the embankment the suction progressively increased during the first test stage as the soil dried tending to hydrostatic conditions (e.g. tens. 8 and 10 in Fig. 4). All the tensiometers at the base of the embankment (e.g. tens 3 in Fig.4) registered a suction decrease which eventually turned in positive PWP, as an effect of fluid flow from both the crest embankment and the foundation layer. These phenomena can be well visualized in Figure 6, where isochrones of PWP along the central axis of the embankment at significant time instants are plotted. The hydrostatic distribution is also reported for comparison. The selected time instants are: t_1 =1000 s, t_2 = 6370, t_3 = 9600 s, t_4 = 11810 s, corresponding to 29, 184, 278 and 342 days, respectively. From Fig. 6, it is interesting to note that, at t_2, suction was approaching the hydrostatic in the embankment, while the foundation layer was still consolidating. When the settlement rate due to consolidation was considered sufficiently low ($t = t_2$), water was allowed to flow riverside. As evidenced by the red line (PPT M) in Fig. 4, the river level was raised in two steps: first, up to a water level L equal to 0.6H, where H is the embankment height at the end of consolidation; this level was kept constant up to t_3 (i.e. for about 70 days at the prototype scale). Then L was raised up 0.82H and kept constant for further 1600 s (46 days). For $t > t_4$, the level was lowered. A picture of the model at $t = t_4$ is reported in Figure 7. The measures of M indicate a water level slightly lower than the actual level at the bank slope visible in Figure 7, due to the earth-gravity distortional effect.

The applied loading steps produced excess PWP in the foundation layer, which, as the hydraulic level was kept constant or lowered, restarted the consolidation process, always with almost the same rate. As the water level increased, the embankment was involved in a seepage process landward. The silty sand progressively saturated, as recorded by the tensiometers, starting by those closer to the riverside slope and to the base, then progressively by the others. In fact, the saturation line reached the tensiometer 10 at t_3, without being affected by the first hydraulic loading step at t_2. As shown in Figure 6, at t_3 and t_4, the effect of saturation of the embankment was a progressively reduction of suction.

At t_4 all the tensiometers embedded in the embankment registered positive PWP. When, at $t > t_4$, the river level was lowered, the embankment slowly de-saturated. Lastly, all the measures of suction in the model embankment (Fig. 1) have been interpolated to gain equipotential lines. Figure 8 reports total head contours on the model embankment at t_4; it is evident that the saturation line reached the landside and more than half of embankment resulted fully saturated.

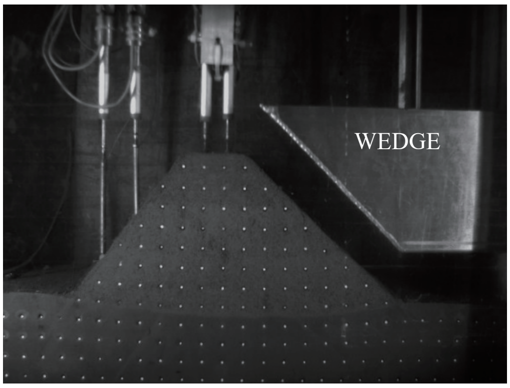

Fig. 3. Model picture at the end of the inflight equilibrium ($t = t_2$).

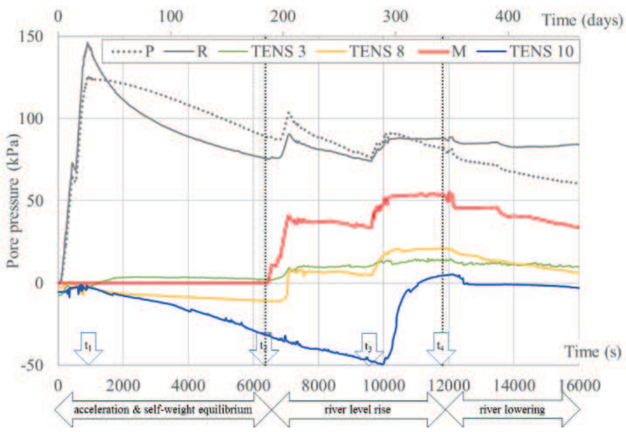

Fig. 4. Time history of the pore pressure at the points located along the central axis of the embankment.

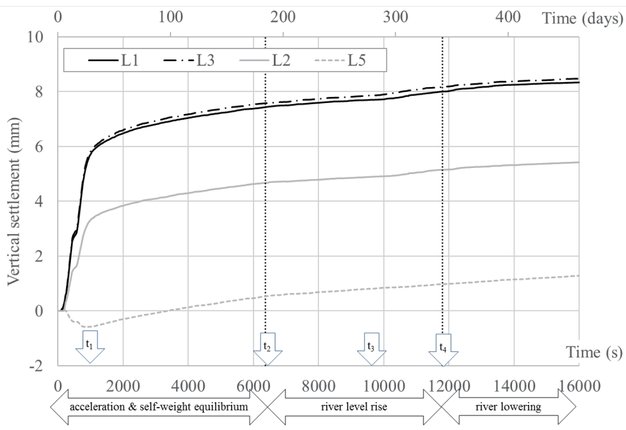

Fig. 5. Time history of the vertical settlement.

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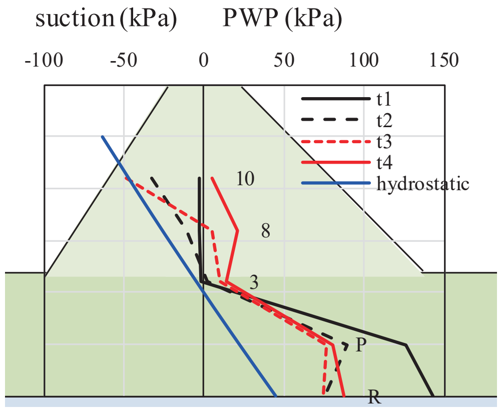

Fig. 6. Profile of suction and pore water pressure at different times along the central axis of the embankment.

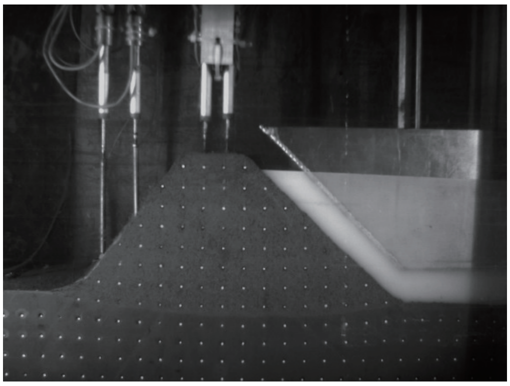

Fig. 7. Model picture at t = t_4.

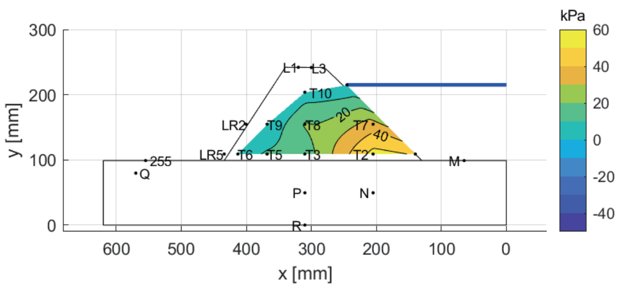

Fig. 8. PWP contour map interpolated by measures of suction in the model embankment at t = t_4.

Regarding the displacements, progressive embankment settlement was measured during acceleration and self-weight equilibrium (Fig. 5), mainly due to the deformation of the foundation layer under the footprint of the embankment (Fig. 3). The maximum settlement rate was observed during the spin-up. As to the embankment, Figure 5 clearly shows that the vertical displacement measured up to t_3 are due to the consolidation of the foundation layer. The settlement rate slightly increased after t_3. However, the effect of the hydraulic loading and unloading was negligible on the embankment stability and no failure mechanism was observed.

4 CONCLUSIONS

In this paper the results of a centrifuge test on a silty sand model embankment compacted in unsaturated conditions and subjected to flooding have been discussed. Looking at the time history of pore water pressure, the saturation line reached the crest only at the start of the second step of flooding, t_3, and the half model embankment result fully saturated at the end of the second step, t_4. Thinking to the time at the prototype scale, the water level reached the landside after very long and unrealistic duration of flood (more than 100 days). This proves that the simplified hypothesis of steady-state seepage for the design and safety assessmentof a river embankment as the model investigated here, is too much conservative. The maximum settlement was observed during the spin-up mainly due to the deformation of the foundation layer while the model embankment behaved in a stiffer manner. The settlements measured during the flooding were negligible and basically related to the consolidation of the foundation layer.

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