Analysis of transient seepage through a river embankment by means of centrifuge modelling

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Abstract. River embankments are mostly partially saturated and the degree of saturation within the body may vary significantly throughout the year, due to the seasonal fluctuations of the river level, infiltrations of meteoric precipitation and evapotranspiration. Given the significant effects of partial saturation on the hydro-mechanical behaviour of soils, realistic assumptions of the state of an embankment are required for proper modelling its response to hydraulic loadings. In this framework, centrifuge modelling is a promising tool to get insight into the saturation conditions of an embankment during flooding events, as it allows the direct observation of phenomena hardly detectable at the prototype scale, thus enabling the validation and calibration of numerical models. In this paper, the results of a centrifuge test carried out on small-scale physical model of a compacted silty clayey sand embankment subjected to flooding, tested at the enhanced gravity of 50 g, are shown and discussed. The physical model was thoughtfully instrumented with potentiometers, miniaturized pore pressure transducers and tensiometers. Pore pressures and suctions measured during the experiment have clearly shown that the steady-state flow conditions are reached only after an unrealistic long simulated flood event. It therefore emerges that, for the design and/or the evaluation of the safety conditions of a river embankment similar to the one tested, the simplified hypothesis of a steady-state seepage could result, in many cases, an excessively conservative assumption.

1 Introduction

Assessing the safety conditions and planning maintenance of earthworks used for hydraulic regimentation and flood protection is a priority for land management and hydrogeological risk mitigation. It is well-known that the seepage flow due to the rising water level in the reservoir can cause the failure of the river embankment [1]. Due to the transient seepage regime established in connection with high water events or as a result of rainfall and evapotranspiration phenomena acting at the soil-atmosphere interface, soil water content and pore water pressures vary over time, significantly affecting the stability conditions of the river embankment. As reported in [2], a groundwater seepage flow in the embankments body during a high-water event can cause destabilization by an increase in the self-weight of the soil, associated with a decrease in effective stress due to a reduction in matric suction. Thus, the study of the hydraulic and mechanical behaviour of river embankments under hydraulic forcing is fundamental to model the effective degree of saturation of soils realistically. According to [3], two main mechanisms can cause settlements of compacted fills in partially saturated conditions: self-weight compression and wetting-induced collapse. Frequently, the wetting-induced behaviour of compacted soils, such as those used for river embankment construction, provides a volumetric collapse [4] which depends on the compaction degree. Therefore, experimental procedures to study the hydromechanical behaviour under partially saturated conditions of compacted soils used for the construction of earthen structures are essential for the proper prediction of wetting-induced deformations and of the overall embankment response to hydraulic loadings.

In this regard, the improvement of predictive capabilities of the safety conditions of existing earthen structures can be pursued through the interpretation of data obtained from monitoring activities. However, field data of the river embankment under extreme hydraulic conditions are hard to get. Within this context, the small-scale physical modelling of earth structures under critical scenarios can provide valuable insights. In literature, some centrifuge tests have been conducted to study the hydromechanical behaviour of unsaturated embankments subjected to variable water levels. As discussed by [5], the relationship between the pore water

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pressure behaviour and the failure of a river embankment subjected to water level drawdown while [1] analysed the response of a reservoir embankment subjected to increasing water levels. It emerged that the area of the river embankment interested by seepage is partially saturated, and a high rate of increasing water level induces a dramatic increase of the displacement, plastic volumetric strain and risk of the hydraulic fracturing occurring in the core of the embankment [1]. Overall, the physical modelling allows for the direct and detailed observation of physical phenomena occurring at the prototype scale, as well as the validation and calibration of numerical models.

This paper presents a centrifuge test conducted on a small-scale river embankment consisting of compacted silty sand under unsaturated conditions and subjected to a simulated flood event. The outcomes of the test are herein presented and discussed.

2 Centrifuge test

2.1 Materials

The centrifuge test was performed at the *Istituto Sperimentale Modelli Geotecnici* - ISMGEO (Bergamo, Italy), which hosts a 240 g-ton centrifuge with a nominal radius of 2.20 m and it can spin up a model of 400 kg up to 600 g [6].

A prismatic container, whose internal dimensions are: length = 620 mm, height = 445 mm, width = 160 mm, and with a front wall made of transparent Perspex, has been used for the reconstruction of the model, allowing for direct observation of the physical model during the test through real-time video recordings.

In the test performed, a target acceleration of 50g was applied at the container base, so a geometric scaling factor N equals 50, according to [7].

The model river embankment was prepared by using a mixture [8-9] composed of 70% by dry weight of Ticino sand (TS4 - [10-11]), and 30% of Pontida clay (PON – [8, 12-13]). The grain size distributions of the testing soils are shown in Fig. 1. The mixture is a silty clayey sand, while the PON is a kaolinitic clayey sandy silt obtained from a quarry located in Pontida (Italy). These soils were selected because the riverbanks of the tributaries of the Po River (Italy) are frequently made up of a heterogeneous mixture of sand, silt and sometimes clay, and frequently founded on clay and silty deposits of alluvial environments.

Soils used for the construction of river embankments are commonly compacted to obtain adequate permeability and shear strength properties, so the embankment model was compacted in four layers to the optimum Proctor Standard. The hydromechanical properties of the mixture are discussed in [8-9]. Mechanical and physical parameters assigned to the embankment body and foundation units according to advanced soil constitutive models are reported in [14].

The river embankment was founded on a 100 mm thick, saturated layer of PON (5 m prototype scale). A slurry of PON was prepared with a water content of 1.75 times the liquid limit (Table 1) and consolidated under an effective vertical stress of 200 kPa. The foundation layer was cut, vacuum-packed and placed in the centrifuge container.

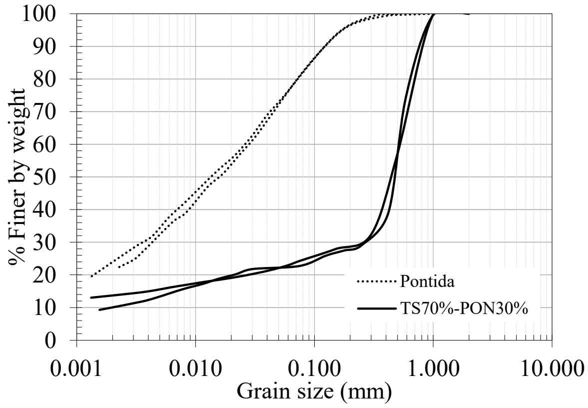


Fig. 1. Grain size distributions of the testing soils (after [8]).

The main physical properties of the soils in testing conditions are listed in Table 1.

Table 1. Physical properties of the testing soils in the model conditions.

	Pontida	**TS70%-PON30%**
Specific unit weight, G_s (-)	2.744	2.684
Liquid limit, LL (%)	23.61	17.66
Plastic limit, PL (%)	13.13	10.23
Plasticity index, PI (%)	10.48	7.42
Unit dry weight, γ_d (kN/m^3)	17.00	20.6
Water content, w (%)	21.00	8.80

2.2 Geometry and instrumentation layout

The geometry of the physical model is shown in Fig. 2. The river embankment is 150 mm high (7.5 m prototype scale) and inclined at 45° and 56° on the river and landside, respectively. To prevent leakage of the pore fluid through interface between the model container and the model embankment, silicon grease was spread on the inside surface of the container walls.

The embankment was instrumented with: eight miniaturised tensiometers (labelled as 2, 3, 5-10 in Fig. 2) capable of measuring suctions up to 500 kPa and suitable for measuring both positive and negative pressures; two linear displacement transducers (L1 and L3) to monitor the vertical displacements of the crest; two roto-translative sensors (LR2 and LR5) to measure the displacements of the bank of the river embankment on the landside. In addition, four pressure transducers (PPTs) (named N, P, R, Q) were housed in the foundation layer and two more PPTs monitored the riverside (M) and landside (255) water levels. The technical specifications of the instruments used are reported in Table 2. PPTs and tensiometers were saturated before being located within the model. Target markers were embedded in the frontal section of the embankment, exposed by the transparent window for digital image analysis. The model geometry and instrument layout are illustrated in Fig. 2.

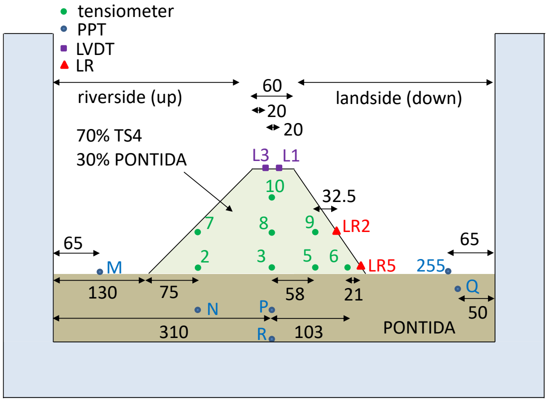


Fig. 2. Physical model geometry (length unit in mm) and instrument layout (PPT: pore pressure transducer, LVDT: linear variable differential transducer, LR: roto-translative sensor).

Table 2. Technical features of the instrumentation.

Instrument	Full scale	Measure range	Sensibility
Tensiometer	500 kPa	± 500 kPa	0.16 mV/kPa
PPT	1500 kPa	0 :1500 kPa	0.07 mV/kPa
LR	45°	± 45°	0.01 mV/°
LVDT	50 mm	0: 50 mm	0.01 mV/mm

2.3 Test procedure

Once the model was reconstituted, it was accelerated to the target angular velocity in two steps until the time t_1, as showed in Fig. 3 (black line) and then kept constant until the end of the test. After the consolidation phase (from t_1 to t_2) provoked by the increment of the angular velocity, the reservoir water level was increased in order to study the hydro-mechanical response of the earthen structure. As reported in Fig. 3 (blue line, PPT M), the hydraulic loading was applied in two steps: raising of the river level (from t_2 to t_4) and partial emptying (after t_4) (see x-axis in Fig. 3). The highlighted time instants are: t_1 =1050 s, t_2 = 6370, t_3 = 9630 s, t_4 = 11810 s at the model scale. As shown by the blue line in Fig. 3, the river level was increased in two phases: first, up to a water level L equal to 0.6H, where H is the height of the river embankment at the end of the consolidation; this level was kept constant until t_3 (i.e., for approximately 70 days at prototype scale). Then, the river level was increased to 0.82H and kept constant for a further 1600 s (46 days at prototype scale) to reach the stationary conditions.

To clarify the time scaling issues due to the presence of an enhanced gravity field, the most significant time steps highlighted in Fig. 3 are reported at the model scale.

The fluid used to apply the hydraulic loadings (i.e., water mixed with a white pigment to improve visibility) was stored in a tank outside the centrifuge and connected to the model via a pipe. It was allowed to flow inside the centrifuge basket through a hole drilled in its wall at the level of the toe of the embankment. The flow was controlled with a valve and the fluid level was monitored with the PPT M (Fig. 2). Once a target flood level was reached, the valve was closed, and the hydraulic head was further adjusted using a hydraulically actioned wedge shown in Fig. 4.

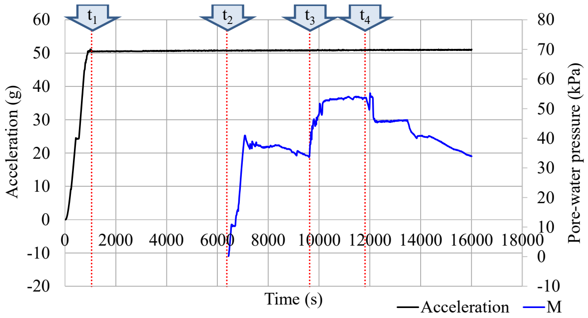


Fig. 3. Centrifuge test phases (time at model scale).

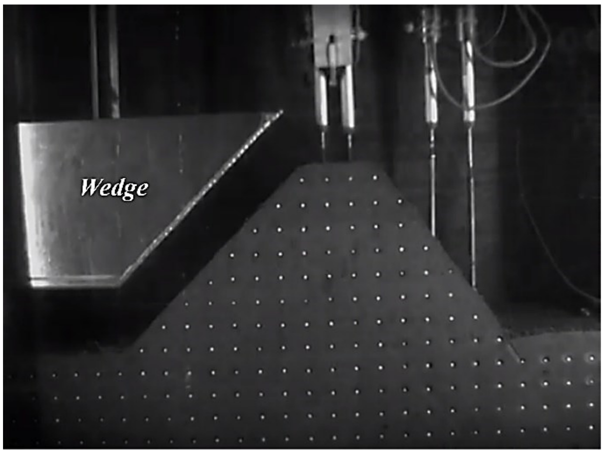


Fig. 4. Physical model at the beginning of the test (after [15]).

3 Experimental results

The time histories of vertical displacements of the embankment crest and the monitored points on the landside are shown in Fig. 5. A progressive settlement of the embankment of approximately 8 mm (0.38 m at prototype scale - Fig. 5) was observed during the centrifuge rotation and model consolidation phases, mainly due to the deformation of the foundation layer under the footprint of the river embankment. As seen, also through direct observation of the model by means of digital image analyses of photographs that allowed the reconstruction of the displacements of the markers included in the model (white points in Fig. 4), the horizontal strains were minimal compared to vertical ones.

An increase of approximately 1 mm of the settlements was recorded after t_3 because of the increasing water level. It can be observed, by the comparison with the blue line in Fig. 6 (PPT M), that displacement velocities do not increase in proportion to the speed at which the water rises. Similarly, no significant changes in settlements were observed during the partial emptying. Therefore, the effect of the hydraulic loadings did not compromise the river embankment stability; in fact, no failure mechanism was observed [15]. However, it is well known that structural failures may require a combination of triggering factors, such as floods and deterioration symptoms as animal and/or anthropic damages [16-17] that herein have been disregarded.

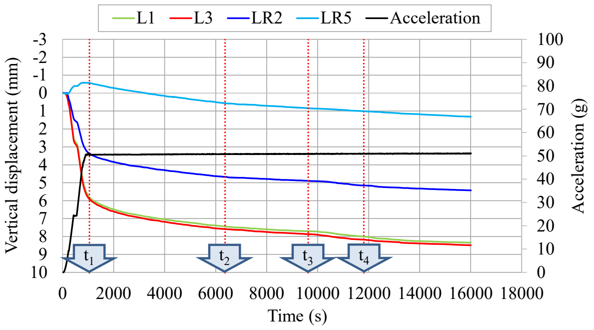


Fig. 5. Vertical displacements (time at model scale).

Fig. 6 shows the time history of the pore water pressures (PWPs) and suction measured during the test by the sensors positioned in the foundation (Fig. 6a), at the base (Fig. 6b) and in the middle-top of the river embankment (Fig. 6c). The measurements of PPT M and the time history of the acceleration imposed at the base of the model are also reported in Fig. 6.

During the first phase of the test, because of the increasing acceleration, a positive overpressure of the PWP was generated in the foundation layer (PPTs N, P and R in Fig. 6a), which, once the target acceleration was reached, began to equalize towards the equilibrium condition (hydrostatic distribution).

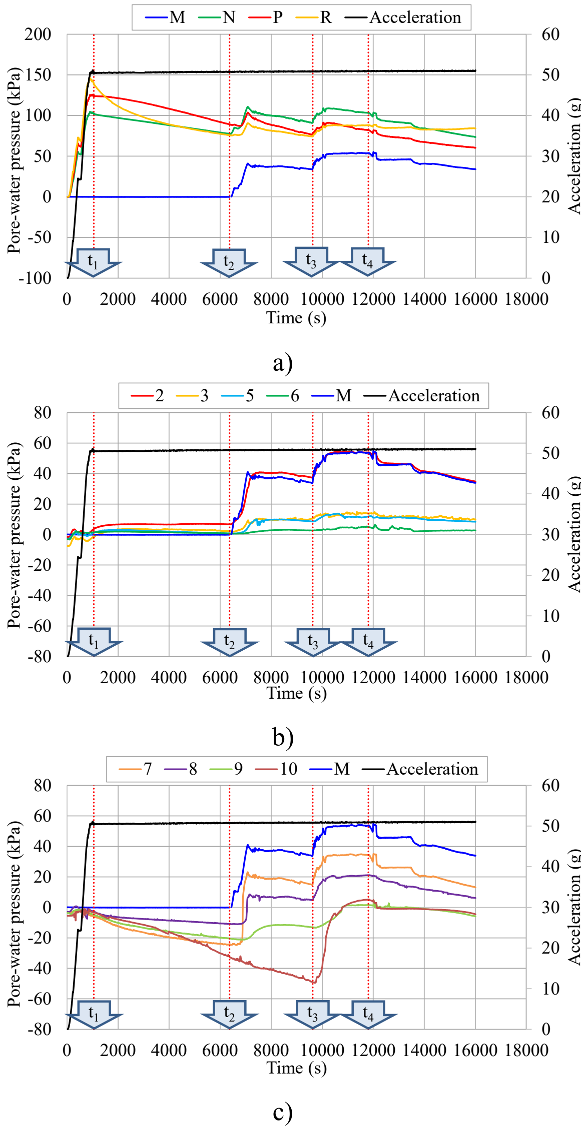
After the consolidation phase ($t>t_2$), hydraulic load variations produced overpressure of the PWPs in the foundation layer, which began to dissipate during the persistence of the river level, thus restarting the consolidation process. During the partial emptying, the PWPs in the foundation decreased with different gradients at the control points.

Regarding the river embankment, all tensiometers recorded an initial suction of approximately 5 kPa (Fig. 6), confirming the suction measured on the mixture after compaction reported in [8].

During the first two phases of the test, in the upper part of the embankment, the suction increased progressively (tensiometers in Fig. 6c), while all the tensiometers at the base of the river embankment (Fig. 6b) recorded a decrease in suction until a positive PWPs were reached, because of the filtration from the foundation layer to the embankment.

During the river level raising, a filtration towards the landside occurred. As recorded by the tensiometers, first by those closest to the riverside and the base, then progressively by the others, the river embankment gradually increases saturation. Pore water pressures quickly established in the river embankment, apart close to the crest (tens. 10), already at the first increase in hydraulic load ($t > t_2$).

The saturation line reached tensiometer 10 near the crest of the river embankment after t_3 (94 days at the prototype scale after the river level raising start) without being affected by the first increase in hydraulic load at t_2. However, when the river level dropped at $t > t_4$, the river embankment was desaturated, especially close to the tensiometers placed at the top and in the middle-top of the river embankment.



a)

b)

c)

Fig. 6. Pore water pressures (time at model scale): a) foundation; b) at the base and c) in the middle-top of the river embankment.

The filtration phenomena involving the embankment and foundation during the flooding phase can be well understood by observing the PWP isochrones at the central vertical axis of the embankment (red vertical line in Fig. 7) and at the vertical section close to the riverside (green vertical line in Fig. 7) at three significant time instants (i.e., t_2, t_3 and t_4). Equipotential lines obtained by interpolating the PWPs along each vertical are shown for the same time instants in Fig. 7a.

Before the river level raising phase, suctions up to about 50 kPa are recorded in the embankment tending towards a hydrostatic condition. In the model, at t_2, only the tensiometers placed in the horizontal base section (tens. 2 and 3 in Fig. 7) measure positive PWPs; at t_4, all tensiometers measure positive PWPs, confirming the advancement of the saturation line. In fact, as the river level increases (from t_2 to t_4), a seepage process establishes in the river embankment towards the landside. The second step of hydraulic loading further increases the PWPs towards positive values, lowering the significant suction values at the river embankment crest, which are reduced to zero over the second persistence. By observing Fig. 7b, over pore pressures in the foundation layer are always appreciable with respect to hydrostatic conditions, pointing out that the consolidation phase is not yet completed.

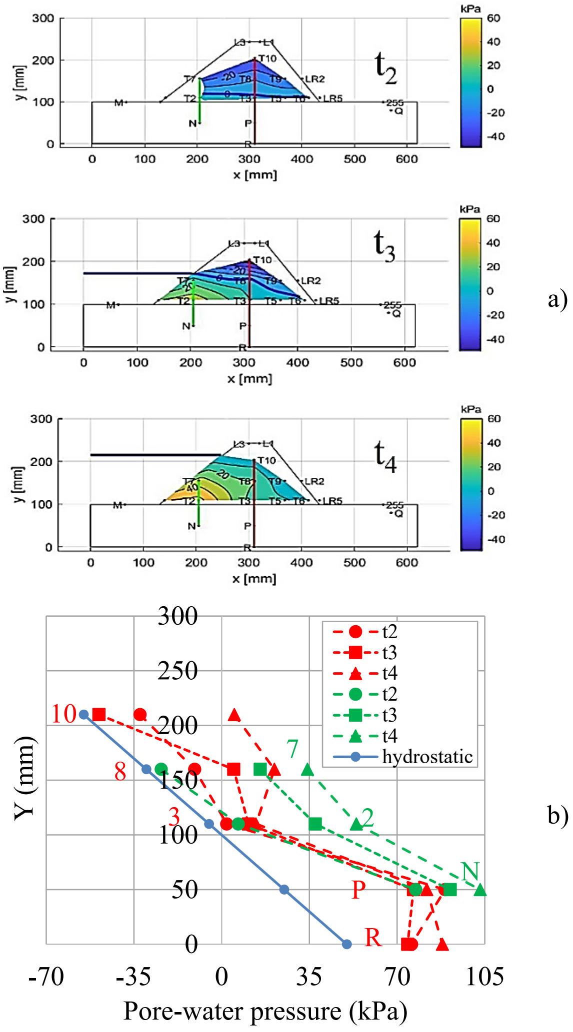


Fig. 7. Experimental results: a) contours of equipotential lines and b) pore water pressures profile along two vertical sections at different times during the river level raising.

4 Concluding remarks

The paper discussed the results of a centrifuge test on a river embankment model of a silty clayey sand, compacted under partially saturated conditions and subjected to hydraulic loadings. The river embankment is founded on a fully saturated Pontida clayey sandy silt. The model was instrumented with displacement and pressure transducers and tensiometers to monitor the change in pore pressure and matrix suction during the progressive increase of the flood level and the subsequent saturation of the embankment. The analysis of the monitoring data allowed to catch the hydro-mechanical behaviour of the river embankment during the test.

The maximum settlement of the embankment body was observed during the initial spin-up phase, mainly due to the deformation of the foundation layer, while the embankment had a relatively rigid behaviour. The settlements measured during the spin-up phases were negligible and still related to the consolidation process in the foundation layer. In addition, observing the time history of pore water pressures, it can be noted that the embankment resulted almost fully saturated at the end of the second rise in river level.

At the prototype scale, the water level reached the landside after an unrealistic persistence of the hydrometric peak of about one hundred days, providing experimental confirmation that the simplified assumption of filtration under steady-state conditions, typically used for riverbank design, can generate overly conservative results in most cases.

The physical model, respecting the scaling laws, reproduced the prototype and allowed the direct observation of physical phenomena that usually occur in riverbanks, which experience states of partial saturation for a large part of their service life. Finally, the results of this centrifuge test represent a useful dataset for calibrating a predictive model and provide some meaningful indications for the design and maintenance of earthworks.

Acknowledgments 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).

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