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

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Abstract. Earthen river embankments are typically in unsaturated conditions during their lifetime and the degree of saturation within their bodies may vary significantly throughout the year, due to seasonal fluctuations of the river stage, as well as infiltrations of meteoric precipitation and evapotranspiration phenomena. Given the significant effects of partial saturation on the hydro-mechanical behaviour of soils, realistic assumptions on the actual water content distribution inside the embankments are essential for properly modelling their response to hydraulic loadings. In this framework, centrifuge modelling is a useful tool to get insights into the evolution of saturation conditions of a water retaining structure during flood events. It allows for the direct observation of the groundwater flow process, which is hardly detectable at the prototype scale, enabling, at the same time, the validation and calibration of predictive numerical tools. 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 a simulated high-water event, at the enhanced gravity of 50-g, are presented and discussed. The physical model was carefully instrumented with potentiometers, miniaturized pore pressure transducers and tensiometers. Pore pressures and suctions measured during the experiment showed that the stationary flow conditions were reached only after an unrealistic hydrometric peak persistence. It therefore emerges that, for the design and/or the assessment of the safety conditions of a river embankment similar to the one tested, the simplified hypothesis of a steady-state seepage, in equilibrium with the maximum river stage expected 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 use management and hydrogeological risk mitigation. It is well-known that the groundwater flow due to the river stage rising may cause the failure of the weakest section of water retaining infrastructure [1]. Due to the transient seepage regime established in connection with high water events or because 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], groundwater seepage flow in the embankments body during a high-water event can cause sudden collapses triggered by an increase in the self-weight of the soil, associated with a drop in effective stress, due to a reduction in matric suction. Thus, the study of the actual hydraulic behaviour of river embankments under simulated high-water events is fundamental to realistically model its mechanical response. According to [3], two main mechanisms can cause settlements of compacted fills in partially saturated conditions: self-weight compression and wetting-induced collapse. In the case of compacted soils such as those used for river embankment construction and reinforcement, this last mechanism frequently prevails, resulting in a volumetric collapse, i.e. in a rapid settlement of the partially saturated soil, due to the increase of water content at essentially constant total vertical stress [4]. Therefore, experimental procedures aimed at investigating the hydromechanical behaviour of unsaturated earth 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 river embankment response under extreme hydraulic conditions are hard to be collected. For this reason, centrifuge testing on small-scale physical models of earth structures under critical scenarios has

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gained increasing importance since they can provide valuable insights on the mechanical and hydraulic behaviour of partially saturated soils. Some tests have been focused on the response of unsaturated embankments to variable water levels imposed. A series of models were subjected to a planned sequence of rapid perturbations of hydraulic loadings up to failure, using the beam centrifuge of the University of Cambridge for determining the causes of the collapses occurred to river Thames flood embankments in late seventies [5]. Narita et al. [6] discussed the relationship between the pore water 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 volume 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].

Important aspects to account for in centrifuge physical modelling of unsaturated soil behaviour are related to scaling laws, sample preparation and boundary condition; [7] presented the results of several authors on these topics and highlighted that centrifuge models can well predict collapse of compacted soils and short term expansion, and that diffusion process governing the flow can be conveniently simulated, thanks to the reduction of time by the square of the geometrical scale factor. 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 [8].

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 50-g was applied at the container base, so a geometric scaling factor N equals 50, according to [9].

The river embankment model was prepared by using a mixture [10-11] composed of 70% by dry weight of Ticino sand (TS4 - [12-13]), and 30% of Pontida clayey sandy silt (PON – [10, 14-15]). The grain size distributions of the testing soils are shown in Fig. 1. The mixture is a silty clayey sand, while PON is a kaolinitic clayey sandy silt obtained from a quarry located in Pontida (Italy). These soils were selected to reproduce the stratigraphic layout of the riverbanks of the tributaries of the Po River (Italy), which are frequently composed of a heterogeneous mixture of sand, silt and sometimes clay and commonly founded on clay and silty deposits of alluvial environments. Soils used for the construction of river embankments are usually compacted to obtain adequate shear strength properties and to reduce the permeability, so the embankment model was compacted in four layers to the optimum Proctor Standard water content and dry density. The hydro-mechanical properties of the mixture are discussed in [10-11]. Mechanical and physical parameters assigned to the embankment body and foundation units according to advanced soil constitutive models are reported in [16].

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.

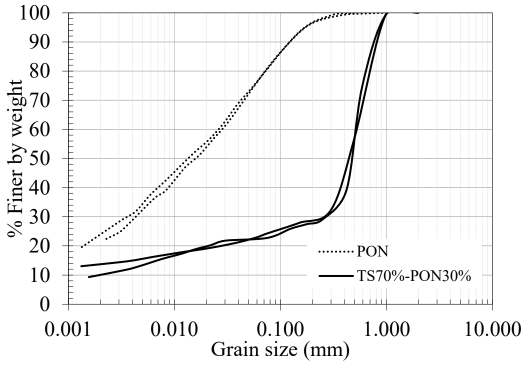

Fig. 1. Grain size distributions of the testing soils (after [10]).

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.

	PON	**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 was 150 mm high (7.5 m prototype scale), with a slope inclination of 45° on the riverside and 56° on the landside. To prevent leakage of the pore fluid through the interface between the model container and the embankment, silicon grease was spread on the inner surface of the container walls.

The embankment was equipped with instruments including: eight miniaturised tensiometers (labelled as 2, 3, 5-10 in Fig. 2); 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) labelled N, P, R, and Q were housed in the foundation layer, and two additional PPTs monitored the water levels on the riverside (M) and landside (255). The technical specifications of the instruments used are reported in Table 2.

In particular, the tensiometers employed are low-cost miniature sensors developed by [17] for applications in centrifuge. They are constructed using the MS54XX series of sensors from Measurement Specialties™, equipped with ceramic discs (air entry value lower than 600 kPa) sealed with an epoxy resin specifically selected to minimise water absorption. Calibration of the tensiometers demonstrated that the sensors are capable of measuring suctions up to of 500 kPa and are suitable for measuring both positive and negative pressures. Tensiometers have to be oven dried after each application. Similarly, like the PPTs, they were saturated before being located within the model. Targets, used as 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.

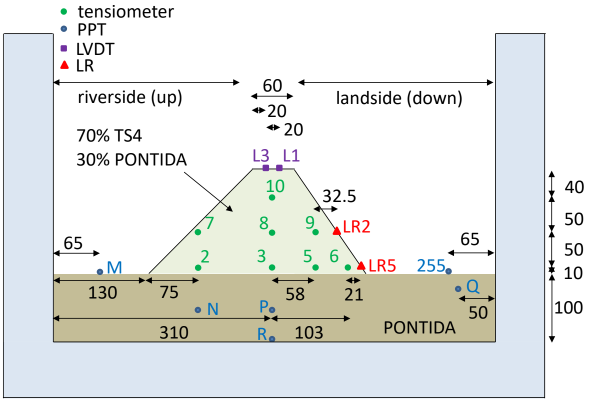

Fig. 2. Physical model geometry (length unit in mm) and instrument layout (PPT: pore pressure transducer, LVDT: linear variable differential transducer, LR: roto-translative sensor).

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 the acceleration was kept constant until the end of the test. After the consolidation phase (from t_1 to t_2), provoked by the increment of the self-weight, the 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 (water mixed with a white pigment to improve visibility) was stored in a tank located outside the centrifuge, about two meters above the rotating symmetric arm (at 1-g), to guarantee adequate water head. Thanks to the shape of the arm characterised by the absence of a central shaft, a pipe running close the rotation axis was used to connect the tank to the container, through a hole drilled in wall, at the level of the toe of the embankment. The flow was controlled with a valve and the fluid level was real-time monitored with the PPT M (Fig. 2). Once the target water level was reached, the valve was closed, and the hydraulic head was further adjusted using a hydraulically actioned wedge, shown in Fig. 4. The scope of the wedge was to reduce the volume of water to be introduced in the model and to allow rise and drawdown of the river level according to a desired rate.

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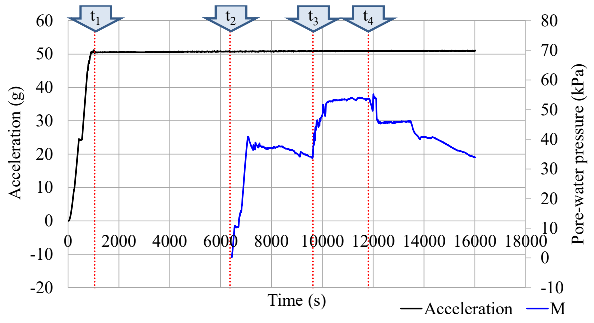


Fig. 3. Centrifuge test phases (time at model scale).

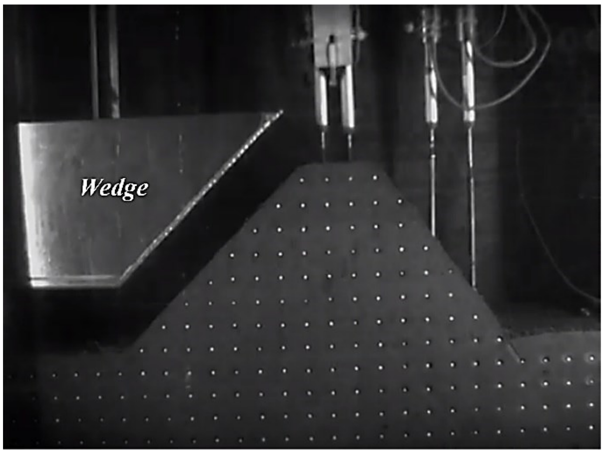


Fig. 4. Physical model at the beginning of the test (after [18]).

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. During centrifuge rotation and model consolidation phases, a progressive settlement of the embankment of approximately 8 mm (0.38 m at prototype scale - Fig. 5) was observed, mainly due to the deformation of the foundation layer beneath the river embankment's footprint. As seen, also through direct observation of the model by means of digital image analyses of frames 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. The initial heave of LR5 was due to an initial swelling of the foundation soil (probably occurred at constant volume), which then slightly settled during the following consolidation stage.

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 [18]. However, it is well known that structural failures may require a combination of triggering factors, such as a long persistence of a hydrometric peak, together with local weaknesses ascribable to soil heterogeneity, wildlife activities, such as animal burrowing, and/or anthropic damages [19-20], herein disregarded.

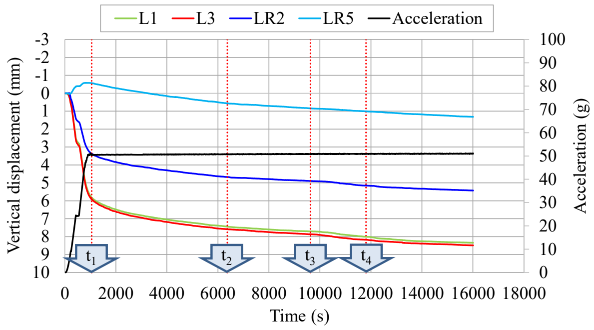


Fig. 5. Vertical displacements (time at model scale).

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, when the centrifuge acceleration was rapidly increased to the target value, PWP quickly increased in the foundation layer (PPTs N, P and R in Fig. 6a), as consequence of the undrained response of the fine-grained layer to the sudden increase of the self-weight. The undrained response caused PWP in excess respect to the equilibrium value corresponding to the hydrostatic distribution. Once the target acceleration was reached, PWP began to reduce towards the equilibrium configuration and the foundation layer underwent through a consolidation process. The hydraulic loading was started when the settlement rate was considered sufficiently low, even if the consolidation of the fine layer was still not concluded.

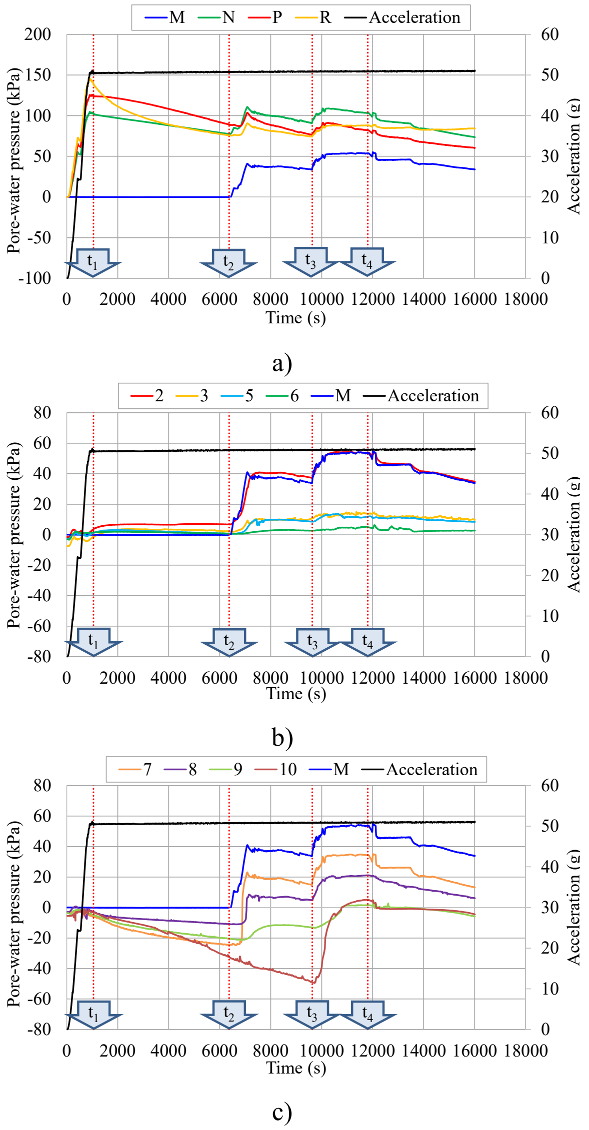
After this phase ($t>t_2$), hydraulic load variations produced again excess pore water pressures in the foundation layer, which began to dissipate during the persistence of the river level, thus restarting the consolidation process. During the partial emptying, the PWPs in the foundation decreased with different gradients.

Regarding the embankment body, all the tensiometers recorded an initial suction of approximately 5 kPa (Fig. 6), confirming the value of suction experimentally measured on the mixture after compaction and reported in [10].

During the first phase of the test, in the upper part of the embankment, the suction progressively increased (tensiometers in Fig. 6c), while all the tensiometers located at the base of the river embankment (Fig. 6b) recorded a decrease in suction until positive PWPs were reached, due to the development of an upward seepage from the foundation layer to the embankment.

During the river level rising, a filtration towards the landside occurred. As recorded by the tensiometers, first by those closer to the riverside and the base, then progressively by the others, the degree of saturation of the river embankment gradually increased. Positive pore water pressures quickly established in the river embankment, except in the crestal area (monitored by tens. 10), already after 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). However, when the river level dropped at $t > t_4$, the river embankment progressively desaturated, as evidenced by 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 seepage phenomena involving the embankment and foundation during the flooding stage can be well understood by observing the PWP isochrones drawn in correspondence of the central vertical axis of the embankment (red vertical line in Fig. 7) and of the vertical section close to the riverside (green vertical line in Fig. 7) at three significant time steps (i.e., t_2, t_3 and t_4). Equipotential lines obtained by interpolating the PWP recordings along each vertical are shown for the same time instants in Fig. 7a.

Before the river level was raised, suctions up to about 50 kPa were recorded at the crest of the embankment, suggesting the trending towards a hydrostatic condition. At t_2, only the tensiometers placed in the horizontal lower section (tens. 2 and 3 in Fig. 7) measured positive PWPs; at t_4, all tensiometers measured positive PWPs, confirming the advancement of the saturation line. In fact, as the river level increased (from t_2 to t_4), a seepage process established in the river embankment towards the landside. The second step of hydraulic loading further increased the PWPs towards positive values, lowering the significant suction values at the river embankment crest, which were almost reduced to zero over the second persistence. By observing Fig. 7b, pore water pressures in the foundation layer have always been greater with respect to hydrostatic conditions, pointing out that the consolidation phase was not yet completed.

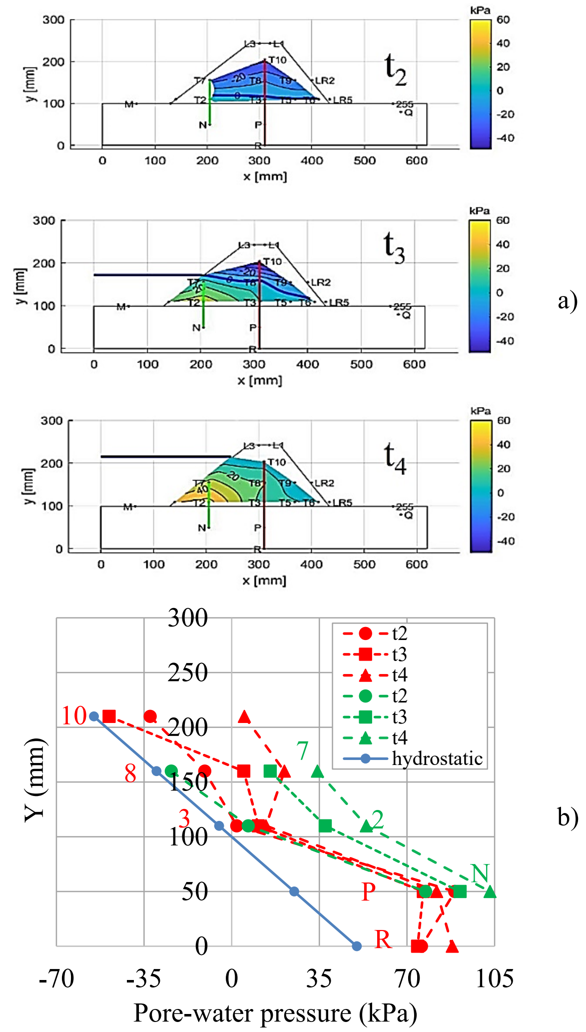


Fig. 7. Experimental results: a) contours of equipotential lines and b) pore water pressures profile along two vertical sections at different times during the river level raising.

4 Concluding remarks

The paper discussed the results of a centrifuge test carried out on a river embankment model made of a silty clayey sand. The model was compacted under partially saturated conditions and subjected to imposed hydraulic loadings.

The maximum settlement of the embankment body was observed during the initial spin-up phase, mainly due to the deformation of the foundation layer under the footprint of the retaining structure. Meanwhile, the embankment showed relatively rigid behaviour and high resistance, due to compaction and the contribution of suction to the shear strength. This prevented the triggering of a failure mechanism, induced by the simulated flood event. The settlements measured during the spin-up phases were almost entirely related to the ongoing consolidation process in the foundation layer.

In addition, by observing the time history of pore water pressures, it can be noted that the embankment was 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. This provides 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.

Thanks to scaling laws, the physical model was able to reproduce a realistic prototype and allowed the direct observation of seepage phenomena that usually occur in river embankments, 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.

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