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Seepage in a flood protection dam – first centrifuge test results

Infiltration dans une digue de protection contre les crues – premiers résultats d'essais en centrifugeuse

G. Portmann*, A. Arnold
Lucerne University of Applied Sciences and Arts, Engineering and Architecture, Institute of Civil Engineering, Horw, Switzerland

Y. Zhang, A. Askarinejad
Delft University of Technology, Geoscience & Engineering, Delft, The Netherlands

**gregor.portmann@hslu.ch*

ABSTRACT: Many flood protection dams in Europe were built more than 100 years ago. These dams often do not meet current flood protection requirements due to increased level of safety requirements, higher damage potential in the valley plains and due to higher peak discharges or water levels expected with changing climatic conditions. A first series of centrifuge tests on an idealized cross-section of a flood protection dam has been carried out in the geotechnical centrifuge at TU Delft in order to study the seepage behaviour of a horizontally layered dam consisting of layers with coarse and fine-grained material. Main aspects of the testing equipment such as a specially manufactured test box which allows to simulate certain flood events of different durations and intensities are presented. Furthermore, measured values of the pore pressure during the investigated flood event, are presented and discussed in comparison to the results of finite element modelling of the dam. Finally, the influence of the hydraulic boundary conditions on the seepage behaviour in the physical and numerical modelling is critically discussed.

RÉSUMÉ: De nombreux digues de rivière en Europe ont été construites il y a plus de 100 ans. Souvent, ces digues en terre ne répondent plus aux exigences récentes en matière de protection contre les crues, en raison des besoins accrues en matière de sécurité, du potentiel de dommages plus élevé et de l'augmentation des niveaux d'eau attendus due au changement climatique. Une première série d'essais en centrifugeuse sur une coupe idéalisée d'une digue de terre a été réalisée dans la centrifugeuse géotechnique de l'Université technique de Delft afin d'étudier le comportement d'infiltration d'une digue stratifiée composée de couches de sol grossier et de sol fin. Les principaux aspects de l'équipement d'essai, tels qu'une boîte d'essai spécialement fabriquée qui permet de simuler certains événements de crue de durées et d'intensités différentes, sont présentés. En outre, les valeurs mesurées de la pression interstitielle pendant la crue étudiée sont présentées et discutées en comparaison avec les résultats de la modélisation par la méthode des éléments finis. Enfin, l'influence des conditions limites hydrauliques sur le comportement de l'infiltration dans la modélisation physique et numérique fait l'objet d'une discussion critique.

Keywords: Centrifuge modelling; seepage; flood protection dam; numerical modelling.

1 INTRODUCTION

Many flood protection dams no longer meet today's safety requirements, especially in the context of climate change. Higher water levels must be expected nowadays. This is illustrated by the example of the flood protection dams along the Alpine Rhine, which are currently being restored in sections. The original straightening and damming of the Rhine started in the 19th century (*Schweizerische Bauzeitung*, 1927) and no longer fulfils flood protection requirements.

A conservative engineering design approach assumes steady-state seepage flow through the dam and is often considered when investigating dam stability or developing measures against stability problems (CIRIA, 2013). However, it seems reasonable to consider transient seepage conditions, as flood events in alpine regions often only have a duration of 12 to 48 h. This could offer a potential for cost minimisation in project planning of remediation measures. Research results on a model river-embankment consisting of silty-sandy material in a geotechnical centrifuge by Giretti et al. (2022) show that the saturation front in the dam reaches the air side of the dam only after a long flood period. Mayor (2013) reports similar results in his large-scale tests at the river Rhône dam, whereas it should be considered that the time until the saturation front reaches the air side depends directly on its permeability and its degree of saturation at the beginning of the flood.

However, if transient flow conditions are to be considered in the design, a more detailed understanding of the evolution of pore water pressure in the dam body is required to ensure safe design. Physical modelling under transient flow conditions can provide valuable data for better interpretation and potentially validation of numerical calculation methods.

A model-dam is used because the construction of a 1:1 scale model dam is complex and costly (Mayor, 2013; Toromanovic et al., 2020). A geotechnical centrifuge is used to increase the acceleration field and thus the effective stresses in the model to ensure comparable results of the model tests with the prototype (Madabhushi, 2014). A geometrically *n*-times smaller dam is subjected to an *n*-times larger *g*-level as the effective stresses are generally accepted to be linearly correlated with depth (Wood, 2004; Askarinejad et al., 2015).

2 METHOD

The focus of the herein described investigation on the flow behaviour and permeability within a layered flood dam lies on the physical centrifuge modelling. Subsequently, a numerical model was created – as would typically be the case in current engineering practise – in order to supplement the experimental results in the sense of a comparative investigation.

2.1 Centrifuge modelling

The experiments were conducted at 100 *g* in the geotechnical centrifuge at TU Delft which has a radius of 1.22 m and a basket size of 400x500x500 mm (Allersma, 1994; Zhang and Askarinejad, 2021). A testing strongbox was created for this purpose. A flood wave could be generated inflight with the help of a water tank and servo coupled valves. In addition, an overflow was placed on the air side of the dam to maintain a constant water level. The model box has outer dimensions of LxHxW = 615x200x120 mm, with 15 mm thick aluminium panels and a transparent front made of 15 mm thick acrylic glass. Figure 1 shows a model dam installed in the test box in the centrifuge basket. The water tank for the flood wave (1.6 litres) is situated on top of the test box. The model dam was constructed according to the prototype of a typical cross-section of the river Rhine dam. On top of the permeable Rhine gravel lies a less permeable layer of flood deposits on which the gravelly dams were built.

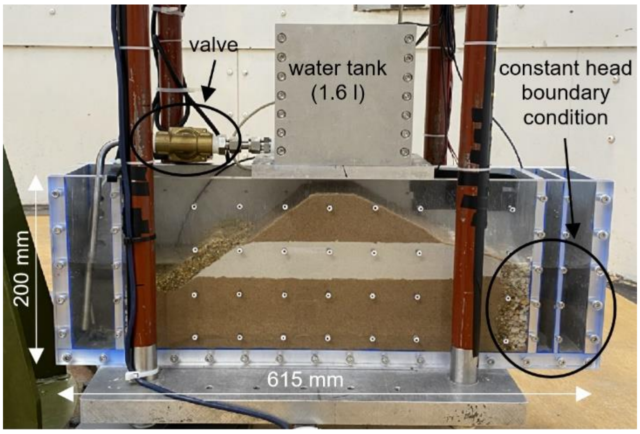

Figure 1. Modell Dam inside the strongbox.

The model dam was constructed at a scale of 1:100 as shown in Figure 2. The crest of the dam is 80 mm higher than the air side terrain and has a base width of approximately 350 mm. It is important that the underlying permeable Rhine gravel is modelled as well since it may influence the seepage behaviour. Geotechnical properties of the materials used in the model are summarised in Table 1. In prototype, the Rhine gravel and the Rhine dam have a similar permeability, so both materials are modelled with Baskarp B25 sand (Pol et al., 2021). For the less permeable layer of flood deposits a mixture of Geba Sand (Maghsoudloo et al., 2021) with 5% Kaolin Clay was used (Figure 2). The permeabilities were determined with constant head tests (Head & Epps, 2011). The values determined in the tests correspond to the vertical permeability k_v.

Table 1. Geotechnical properties of the dam materials used in the centrifuge test.

Soil type	e [1)]	k_v [m/s]	φ'_{cv} [°]
Baskarp B25 Sand	0.69	$6 \cdot 10^{-5}$	32 - 34
Geba Sand with 5% Kaolin Clay	0.64	$2 \cdot 10^{-6}$	~ 31[2)]

[1)] voids ratio after compaction at w = 10%
[2)] value applies for Geba Sand without clay

The soil materials were placed in the model box in layers with a water content of 10% and compacted uniformly. After the entire box was filled, the dam was shaped by removing the excess material. At the same time, samples were taken to check the layer density.

Three Porewater-Pressure-Transducers (PPT) were installed at the bottom of the model (Figure 2) in order to record the propagation of pore water pressure in the dam. In order to check the boundary conditions, two PPTs were installed in the left inlet tank and in the right outlet tank, respectively. Figure 3 shows the planned flood characteristics in the prototype scale for the tests. The water levels refer to the heights from the base of the strongbox (Figure 2). The riverbed accordingly lies at a height of 7.4 m. The goal was to model a flood wave consisting of a pre-wave (13 m), peak (15.4 m) and post-wave (12.3 m) by opening and closing the valves, starting from an initial river level at 9.4 m (steady state with 2 m high river, see Figure 2). Water was used as the fluid for the centrifuge experiments. The model time for seepage processes is therefore reduced by a factor of 1:100^2 (Garnier et al., 2007; Wood, 2004) since the model was tested at 100 *g*. This means that the entire flood event with a duration of 60 h at prototype scale translates to 21.6 s in the centrifuge experiment. The experiments were recorded through the acrylic glass using a digital camera.

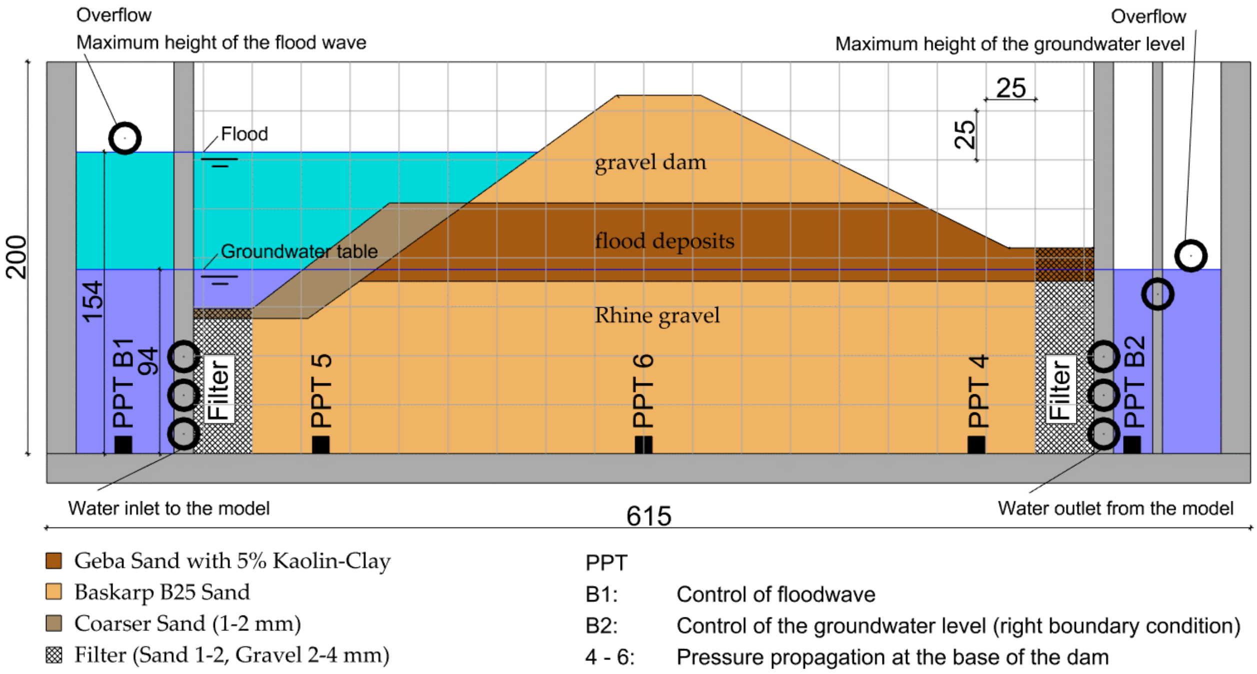

Figure 2. Geometry of the dam built into the test box including positions of PPTs. Dimensions in [mm].

The test procedure is described hereafter with the corresponding prototype time steps, model time is given in parentheses: After the centrifuge reaches 100 *g* (t = 0), the initial water level of 9.4 m (94 mm) is kept constant for 14 d (2 min) to allow stationary conditions to be established. Subsequently, the flood wave is applied stepwise within 60 h (21.6 s) as shown in Figure 3. Finally, the model is kept under 100 *g* for another 35 d (5 min) to restore initial conditions.

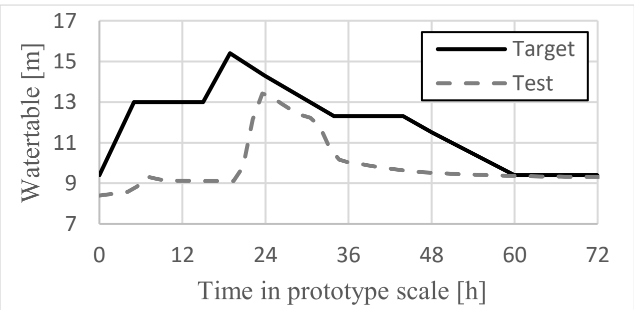

Figure 3. Target hydrograph of the flood wave in prototype scale compared to the actual flood wave achieved during the test (measurement of PPT B1, riverbed is located at 7.4 m).

After the centrifuge test, the model is checked for any signs of erosion, piping processes or stability problems. The initial water table is restored before starting the next test series. However, the desired flood wave could not be achieved because some of the valves could not be opened or closed properly at 100 *g* (Figure 3). Thus, it was difficult to maintain a constant water level with the water available in the tank due to the loss of water through seepage.

2.2 Comparative numerical model

A comparative numerical model of the dam is set at prototype scale in the program PlaxFlow2D from Plaxis with the same boundary conditions as given in the experiment. Special attention was paid to the following points:

- The flood wave is modelled according to the data measured in the centrifuge test (‘Test’ hydrograph in Figure 3).
- The permeable berm on the water side made of coarse sand is not modelled to minimise the computational effort. It is assumed that due to the higher permeability, it does not significantly influence the seepage behaviour.

- A constant head boundary condition is set on the air side as given in the centrifuge model test.
- The FEM model with the corresponding boundary conditions and the mesh is shown in Figure 4.

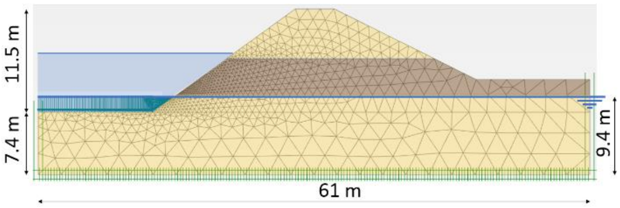

Figure 4. FEM model geometry with mesh and boundary conditions for the PlaxFlow calculation: The initial water level of the river is indicated with blue arrows and corresponds to the height of the constant head boundary condition on the right edge of the model (initially no hydraulic gradient). The variable water level is indicated in blue on the left.

The pressure conditions are compared at points that are always saturated (PPTs in Figure 2). However, it must be assumed that the modelling of the unsaturated dam area above has an influence on the results. For a comparative model, the unsaturated zones of the dam and their behaviour are described using the Van Genuchten (1980) model implemented in the software. Thus, with the help of the dimensionless water content Θ, the relative hydraulic permeability K_r of partially saturated soils can be described:

$$\Theta = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \tag{1}$$

$$K_r(\Theta) = \Theta^{\frac{1}{2}}\left[1 - \left(1 - \Theta^{\frac{1}{m}}\right)^{m}\right]^2 \tag{2}$$

In equation 1, θ describes the actual volumetric water content, θ_r is the residual and θ_s is the saturated volumetric water content. The parameter m is linked to the soil-water retention curve given in Equation 3 as m = 1-1/n:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha \cdot h)^n]^{(m)}} \tag{3}$$

In equation 3, α, n and m are model parameters describing the curvature of the water retention curve after Van Genuchten (1980) and h is the pressure head (suction is positive). However, no soil-water retention curves were available for the materials used. To be able to carry out an approximate calculation and compare it to the centrifuge tests, parameter sets stored in Plaxis were used, see Table 2. The parameter sets were selected on the basis of the particle size distribution in such a way that the numerical calculation models produced the best possible comparison to the centrifuge test results. Due to the chosen procedure, some general points must be emphasised:

- The calculations represent an initial estimate. The actual water retention curves and the associated parameters α and n may differ from those used in the present model.
- A difference between drying and wetting curves can be observed in reality (Benson et al., 2014). This is not taken into account in the numerical model.
- As there is no information on the ratio of saturated horizontal permeability k_h to vertical permeability k_v and a reliable estimate is difficult, no distinction was made.

Table 2. Input parameters for the transient seepage analysis.

	Geba Sand with 5% Kaolin Clay	Baskarp B25 Sand
$k_h = k_v$ [m/s]	$2.3 \cdot 10^{-6}$	$5.0 \cdot 10^{-5}$
e_{init}	0.64	0.69
θ_r	0.01	0.1
θ_s	0.34	0.32
α [1/m]	1.7	5.21
n	1.717	2.374

3 COMPARISON OF RESULTS

The dam did not exhibit any stability problems during the centrifuge tests. Furthermore, it became evident that the entire model (i.e. the centrifuge basket) tilts slightly during the experiments, which results in a water level that is inclined relative to the model box. This phenomenon occurs when the centre of gravity is not in the axis of the centrifuge basket's hinge. However, due to the flood wave and the seepage, the centre of gravity is constantly changing - which explains the phenomenon (the model was installed perpendicular to the flight direction to avoid curvature of the water surface). Thus, at the beginning of the test, the water table at PPT B1 was lower at about 8.4 m than at the end of the test at about 9.3 m (Figure 3). Nevertheless, the propagation of the flood wave through the dam during the centrifuge experiments could be analysed with the help of the PPT measurements, see Figure 5. It is noticeable that there is a significant damping of the flood wave upon entering the dam (see PPT5) and the propagation of the flood wave within the dam is significantly slower on the water side than towards the air side. This becomes clear by comparing the shifting of the pressure peaks over time. The delay between the flood wave and PPT5 is about 5.6 hours, whereas it is only about 3.3 hours between PPT6 and PPT4.

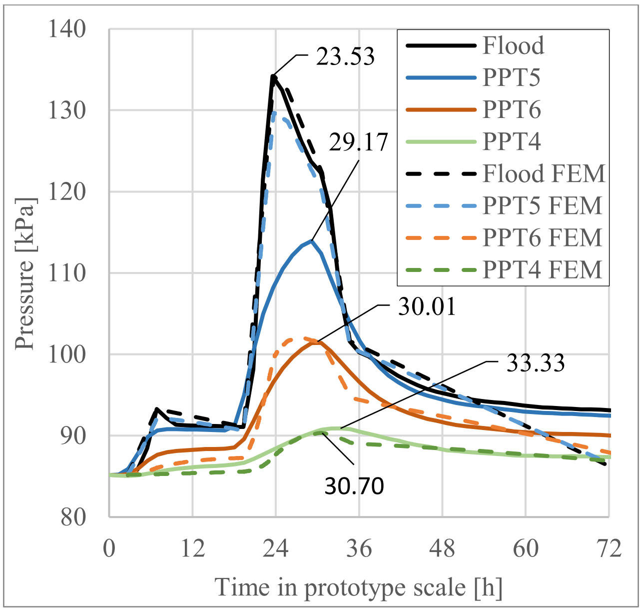

Figure 5. Results of the PPT measurement during the centrifuge tests and comparison with the FEM-simulation. The timestamps of the pressure peaks are indicated in the diagram.

By comparing the pressure changes from the centrifuge test with those from the comparative numerical model (FEM in Figure 5), the following observations can be made: The infiltration behaviour of the numerical model differs significantly from the physical model (PPT5 shows almost no damping in the numerical model compared to the data from the centrifuge test). Nonetheless, PPT6 and PPT4 show relatively good agreement at least in the damping of the pressure magnitude. In the centrifuge test it took about 10 hours to reach the maximum pore pressure at the air side of the dam (peak of PPT4 compared to peak of 'Flood'), whereas in the numerical model there are only about 7 hours in between.

4 CONCLUSION

A difference in time of rise and magnitude of the pore water pressure due to high water levels was observed between the physical model test and the comparative FEM simulation (Figure 5). The difficulties in predicting the pore water pressure distribution and the development of the saturation front in dams were already pointed out by Vaughan (1994) in his Rankine lecture, since most models do not take stress dependent permeability in terms of overburden pressure and heterogeneity of the material into account. In addition, there are considerable uncertainties in soil permeability measurements (anisotropy etc.). The largest deviations between the numerical model and the centrifuge test are found on the water side of the dam. The numerical model overestimates the speed at which the flood wave infiltrates the dam and underestimates the damping of the pore water pressures on the water side.

A further topic to be addressed is the influence of the hydraulic boundary conditions, as it is reasonable to assume, that the type of the air side boundary condition not only has an influence on the dam stability, but also on the overall seepage behaviour. This is particularly relevant as the centrifuge tests are intended to represent the conditions within the prototype dam in order to more realistically portray the behaviour under flood conditions. The tests presented in this paper are based on hydraulic boundary conditions on the air side of the dam corresponding to a constant hydrostatic water pressure (Figure 6 a).

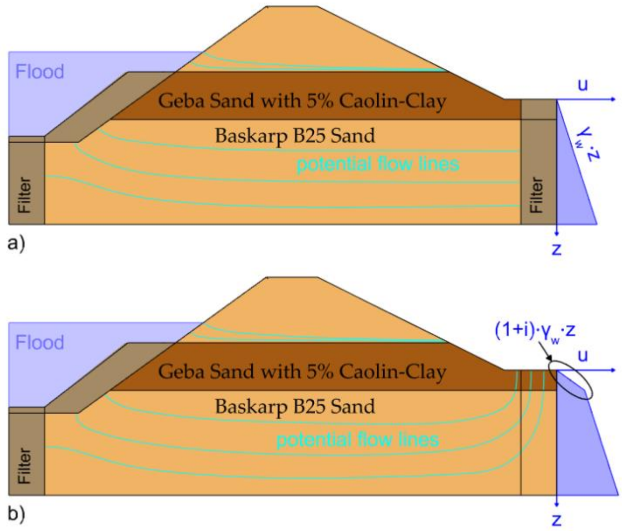

Figure 6. Variation of the boundary conditions on the air side of the dam and their potential influence: a) constant head boundary as modelled in the first test series; b) impermeable boundary – excess pore water pressure assumed below the interlayer as a result.

If the dam was constructed on a widespread fine-grained layer, as it is the situation in parts of the Alpine Rhine, some excess pore water pressures may develop beneath the bottom of the dam on the air side during a flood. As an extreme case, there could be a vertical impermeable boundary such as a construction pit closure in the dam footing area, see Figure 6 b. The pore water pressure distribution beneath the bottom of the dam on the air side therefore depends directly on the permeability and the distance of the air-side boundary condition (this applies to models as well as to prototypes) and must be carefully chosen.

The following observations may be considered to improve the results from further experiments:

- More PPTs should be installed on the water side of the dam to better quantify the flood wave propagation into the dam close to the riverbed. This is where the largest differences between centrifuge tests and numerical simulation have been observed.

- The initial degree of saturation of the dam above the seepage line is unknown - but this significantly influences the infiltration time (Mayor, 2013). The installation of tensiometers to measure suction could therefore be advantageous.
- The intended flood wave, which is inspired by real flood events, could not be achieved due to the complexity of the test control. If the flood wave characteristics are to be simplified for further tests, possible saturation changes of the dam before the flood should be considered.
- It should be considered whether the test may be carried out with viscous fluid instead of water to reduce the time scaling factor (Wood, 2004). This could help to simplify the experimental control and data collection.

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REFERENCES

Allersma, H. G. B. (1994). The University of Delft geotechnical centrifuge. *Centrifuge '94: Proc. of the Int. Conf.*, 47-52.

Askarinejad A., Beck A., and Springman S.M. (2015). Scaling law of static liquefaction mechanism in geocentrifuge and corresponding hydromechanical characterization of an unsaturated silty sand having a viscous pore fluid. *Canadian Geotechnical Journal*. 52(6): 708-720. https://doi.org/10.1139/cgj-2014-0237.

Benson, C. H., Chiang, I., Chalermyanont, T., & Sawangsuriya, A. (2014). Estimating van Genuchten Parameters α and n for Clean Sands from Particle Size Distribution Data. *From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering*, 410–427. https://doi.org/10.1061/9780784413265.033.

CIRIA (ed.). (2013). *The International Levee Handbook*. CIRIA, London.

Garnier, J., Gaudin, C., Springman, S. m., Culligan, P. j., Goodings, D., Konig, D., Kutter, B., Phillips, R., Randolph, M. f., & Thorel, L. (2007). Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling. *International Journal of Physical Modelling in Geotechnics*, 7(3), 01–23. https://doi.org/10.1680/ijpmg.2007.070301.

Giretti, G., Pirone, M., Ventini, R., Mancuso, C., Dodaro, E., Gragnano, G., Gottardi, G., Fioravante, V., & Gabrieli, F. (2022). Centrifuge modelling of a river embankment subjected to transient seepage conditions. *Proceedings of the 10th Int. Conf. on Physical Modelling in Geotechnics. ICPMGE 2024*, Daejeon, South Korea.

Head, K., & Epps, R. (2011). *Manual of soil laboratory testing. Volume 2: Permeability, Shear Strength and Compressibility tests* (3rd Ed.). Wiley, New York.

Madabhushi, G. (2014). *Centrifuge modelling for civil engineers*. Taylor & Francis, Boca Raton.

Maghsoudloo, A., Askarinejad, A., de Jager, R. R., Molenkamp, F., & Hicks, M. A. (2021). Large-scale physical modelling of static liquefaction in gentle submarine slopes. *Landslides*, 18(10), 3315-3335. https://doi.org/10.1007/s10346-021-01705-6.

Mayor, P., A. (2013). *Verhalten eines Flussdammes unter wiederholter Hochwasserbelastung.* Doctoral Thesis, ETH Zürich. https://doi.org/10.3929/ethz-a-010028707.

Pol, J.C., van Klaveren, W., Kanning, W., van Beek, V.M., Robbins, B., & Jonkman, Sebastiaan N. (2021). Progression Rate of Backward Erosion Piping: Small Scale Experiments. *Proceedings of the 10th Int. Conf. on Scour and Erosion*. ICSE-10, Arlington, Virginia, USA.

s.n. (1927). Zur Rhein-Hochwasserkatastrophe. *Schweizerische Bauzeitung*, 89/90 (Heft 16). ETH Zürich. https://doi.org/10.5169/seals-41789.

Toromanovic, J., Lagerlund, J., Viklander, P., & Laue, J. (2020). Geotechnical instrumentation of an experimental embankment dam. 171–176. *Proc. of the 4th Europ. Conf. on Physical Modelling in Geotechnics 2020*, Luleå, Sweden.

Vaughan, P. R. (1994). Assumption, prediction and reality in geotechnical engineering. *Géotechnique*, 44(4), 573–609. https://doi.org/10.1680/geot.1994.44.4.573.

Van Genuchten, M. Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892-898 https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wood, D. (2004). *Geotechnical modelling*. Spon Press, London. https://doi.org/10.1201/9781315273556.

Zhang, W, Askarinejad, A. (2021). Centrifuge modelling of static liquefaction in submarine slopes: scaling law dilemma. *Canadian Geotechnical Journal.* 58(2): 200-209. https://doi.org/10.1139/cgj-2019-0417.