A multi-scale physical approach to investigate the effectiveness of a nature-based solution for mitigating backward erosion piping

E. Dodaro, E. Tumedei, M. Marchi, G. Gottardi, L. Tonni
University of Bologna, Department of Civil, Chemical, Environmental and Materials Engineering, Bologna, Italy, elena.dodaro2@unibo.it;emanuele.tumedei2@unibo.it;michela.marchi@unibo.it; guido.gottardi2@unibo.it;laura.tonni@unibo.it

ABSTRACT: Backward erosion piping is a form of internal erosion that may develop in the foundations of river embankments, due to underseepage. At the ground surface, near the landside toe, this phenomenon typically manifests as sand volcanoes, commonly known as sand boils. The widespread occurrence of the phenomenon in many river embankment systems worldwide (e.g., Po and Danube rivers) highlights the need for effective and sustainable countermeasures. Within the framework of the European LIFE SandBoil project, coordinated by the University of Bologna, a multi-scale experimental programme was envisaged and carried out to validate a nature-based mitigation measure. The investigation began with small-scale laboratory tests, aimed at reproducing the progression of pipes and assessing the effectiveness of vertical pervious barriers as a mitigation technology. This was followed by medium-scale physical modelling, which provided further insights into piping dynamics, under more realistic boundary conditions. Finally, a full-scale experimental setup was recently built at the AIPo Research Centre, located in Boretto (Northern Italy), with the aim of validating the performance of the mitigation solution, prior to implementation in real river embankments. This paper presents the multi-scale experimental physical modelling setups developed within the project, as part of the prototyping activities. The proposed approach is intended to provide a contribution to the enhancement of the resilience of river embankment systems worldwide.

1 INTRODUCTION

Among the internal erosion mechanisms affecting flood defence infrastructures, backward erosion piping is acknowledged as one of the most insidious. River embankment sections susceptible to backward erosion piping are typically characterized by a specific stratigraphic profile, consisting in a permeable sandy *aquifer* overlain by a thin, low-permeability cohesive layer, commonly referred to as *blanket*. The phenomenon may occur at the landside toe of the embankment, where local heterogeneities, defects, or pre-existing cracks promote the concentration of seepage outflow. Subsequently, as a result of intense or repeated high-water events, erosive channels, commonly referred to as *pipes*, develop at the interface between the aquifer and the blanket and progressively advance in the upstream direction, towards the river. A schematic representation of the main stages characterising backward erosion piping is provided in Figure 1.

A clear indicator of an ongoing process is the presence of one or multiple sand boils, near the landside toe at the ground surface, appearing as volcano-shaped cones, formed by the ejection of water and soil particles. As a representative example of the more than 130 documented piping manifestations along the Po River (Tonni et al., 2024), Figure 2 shows a so-called historical sand boil detected at Ro Ferrarese, located in the lower stretch of the watercourse. Occurrences of backward erosion piping have been also reported along several major river systems worldwide, such as the Danube, Rhine, Meuse and Mississippi, where the phenomenon has caused inundation of the rural areas and catastrophic embankment breaches (Semmens and Zhou, 2019).

Over the last decades, extensive physical modelling has been conducted to investigate the onset and evolution of backward erosion piping under controlled laboratory environments. Early contributions led to the development of analytical and semi-empirical models, such as the Sellmeijer approach (Sellmeijer & Koenders, 1991) and the 'Blanket theory' (USACE, 2000), still representing milestones in the engineering practice. Subsequent laboratory experiments have provided significant insights into the factors governing pipe initiation and progression (Schmertmann, 2000; van Beek et al., 2015). Further experimental studies have focused on the influence of boundary conditions, exit geometry and seepage path configuration through a wide range of small and medium-scale experiments (Sellmeijer et al., 2011; Zhang et al., 2022; Ramezanifouladi and Côté, 2024), flume testing (Robbins et al., 2020) and centrifuge modelling, which has enabled the study of piping mechanisms under stress conditions representative of the field scale (Ovalle-Villamil and Sasanakul, 2021; Okamura et al., 2022). On the other hand, full-scale investigations still remain comparatively limited, due to the technical complexities and costs associated to the construction of representative pilot sites. Notable large-scale testing facilities include the 'IJkdijk' and 'Hedwigepolder' sites in the Netherlands (de Vries et al., 2010; van Goor et al., 2022).

This paper presents the multi-scale experimental setups developed in the framework of the European LIFE SandBoil project (https://lifesandboil.eu/), coordinated by the University of Bologna (Italy), to advance the understanding on backward erosion piping and to validate the effectiveness of a nature-based vertical pervious barrier, as a mitigation technology. The project encompasses small and medium-scale physical modelling (Gragnano et al., 2023; Dodaro et al., 2024), as well as full-scale testing (Dodaro et al., 2026), which provides a robust benchmark for validating experimental findings across different scales. In particular, a full-scale pilot embankment was designed and constructed at the AIPo Research Centre in Boretto (Northern Italy), enabling controlled simulation of underseepage conditions and the assessment of the proposed mitigation measure prior to large-scale field implementation.

2 THE SMALL-SCALE EXPERIMENTAL SETUP

The small-scale device, designed and built at the Geotechnical Laboratory of the University of Bologna, shown in Figure 3, consists of a prismatic plexiglass box with transparent sides and top cap, to facilitate the observation of the erosion process from different points of view.

The dimensions of the box are the following: length L = 500 mm, width B = 350 mm and height H = 500 mm. An upstream distribution chamber, equipped with a filter for water-sand separation, is connected to an external reservoir. Top confinement is provided by a 35 mm thick plexiglass plate featuring a 12 mm diameter outlet located 350 mm downstream of the distribution chamber, corresponding to the seepage length.

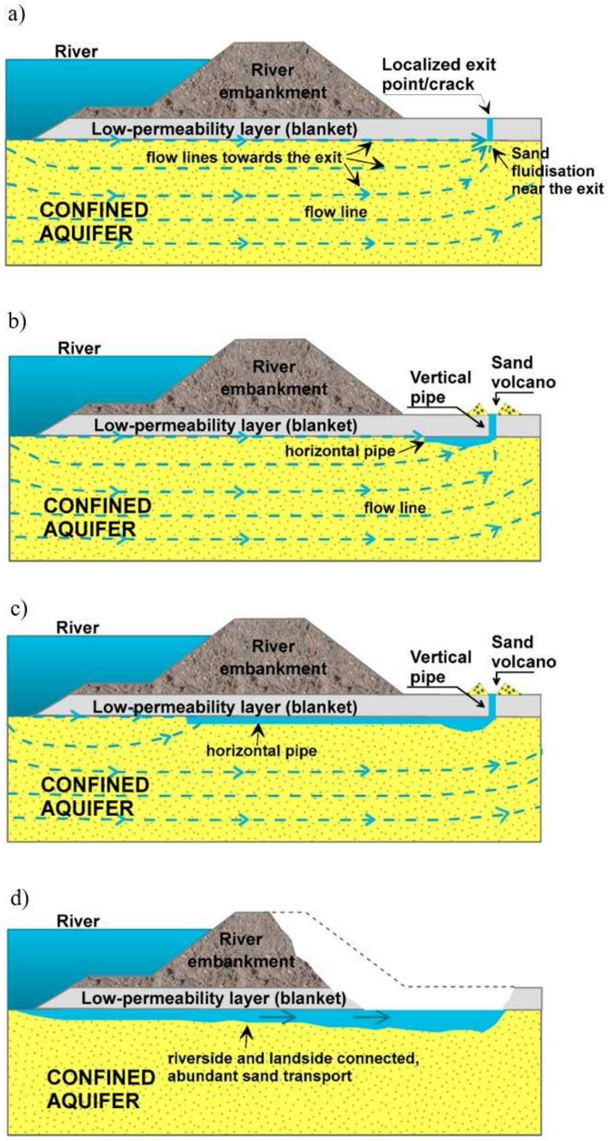

Figure 1. Phases of the backward erosion piping process: a) sand fluidisation around the exit hole; b) onset of backward erosion; c) upstream progression of a horizontal pipe beneath the river embankment; d) progressive widening of the horizontal pipe, ultimately leading to failure.

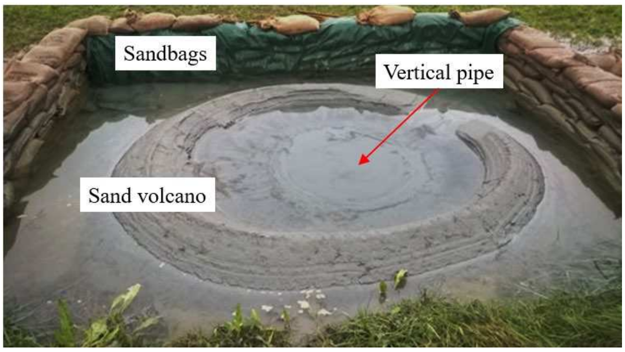

Figure 2. Photo of a sand boil reactivation observed in November 2014 at Ro Ferrarese, along the banks of the Po River, mitigated with sandbags as an emergency countermeasure.

Above the outlet hole, a 3D-printed polylactic acid (PLA) cylinder is placed to collect the eroded sand and maintain a constant downstream head. The hydraulic load control system consists of an overflow device housed within an upstream cylindrical chamber, located above the top cap. Water seeping through the sample is subsequently conveyed to a sedimentation tank, where soil particles are allowed to settle and is then recirculated to the external upstream supply tank.

Pore pressure monitoring is a fundamental component of the experimental setup, as it provides direct insight into the hydraulic conditions governing the development of backward erosion piping. In the LIFE SandBoil small-scale experimental apparatus, three pore pressure transducers connected to the top cap, are used to monitor the hydraulic head along the centreline of the model.

The experimental setup also includes a Keyence FD-H series clamp-on flow meter, used to measure the water discharge exiting the model, through the downstream outlet opening. This sensor operates on a non-contact measurement principle based on the Doppler effect, whereby the flow velocity is determined from the frequency shift of ultrasonic waves scattered by particles or bubbles within the fluid. As a complementary approach, water discharge is also quantified by weighing the outflowing water at predefined time intervals.

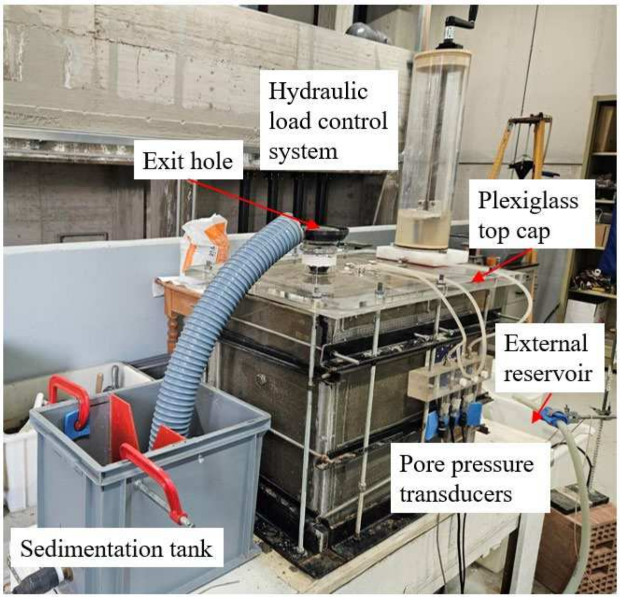

Figure 3. Picture of the small-scale experimental apparatus for investigating erosion phenomena at the Geotechnical Laboratory of the University of Bologna.

A high-resolution camera is mounted on an aluminium frame to enable overhead observation of the top surface of the sample, with particular focus on pipe progression. Adequate and uniform lighting is employed to ensure high image quality. Data from all instruments are continuously acquired and stored by a dedicated workstation. The data logging system ensures comprehensive documentation of each experiment and supporting subsequent analysis.

3 THE MEDIUM-SCALE APPARATUS

The novel medium-scale apparatus, shown in Figure 4a, consists of a stainless-steel prismatic box, in which the sand aquifer is reconstituted. The container is characterized by the following internal dimensions: length L = 2200 mm, width B = 1100 mm and height H = 600 mm. A flow distribution chamber, with a filter to separate water from sand, is located on the upstream side of the box and connected to a top chimney (shown in Figure 4b), which is used to impose incremental hydraulic heads. A second distribution chamber positioned on the downstream side of the box allows the development of horizontal flow lines within the sample. Water used during the test is stored within an external reservoir and conveyed to the box through a hydraulic pipe system equipped with lift pumps. Water levels are kept steady by a bell-mouth shaped spillway, operated by external winch handles.

A 35-mm thick plexiglass cover is placed on the top of the sample, to simulate the fine-grained impermeable layer, featuring an exit hole with an adjustable diameter, representing the vertical pipe. The distance between the exit hole and the upstream chamber, equivalent to the seepage length of the model, is 1800 mm. Eroded sand is collected within a 3D-printed cylinder, placed above the exit hole.

The water recirculation system involves the use of a sedimentation tank, with the aim of removing the sand particles transported by water flow. The monitoring setup includes: i) pore pressure transducers (PPTs), screwed onto the top cover along the centreline and a middle transversal axis, used to monitor the hydraulic head loss associated to pipes progression. An additional PPT, connected to the upstream chamber, is used to record the hydraulic load sequences applied to the sample during the tests. All the PPTs are connected to a stand-alone data acquisition system.

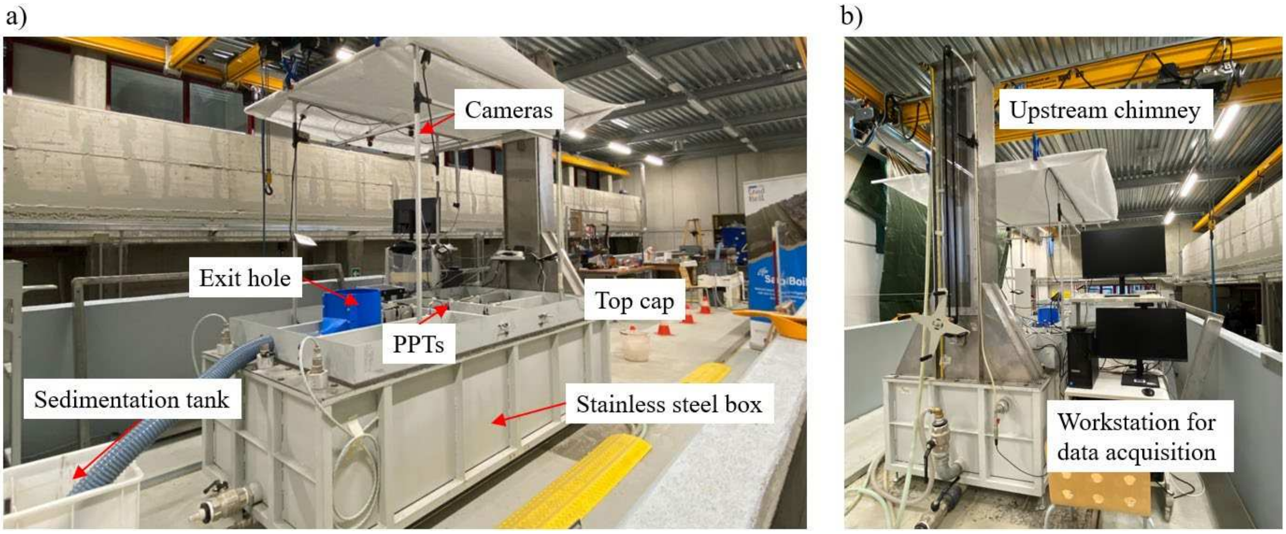

Figure 4. a) General view of the medium-scale experimental setup at the University of Bologna; b) View of the upstream hydraulic load control system.

ii) Three high-definition cameras mounted on a support structure, along with four spotlights, and oriented orthogonally to the flow direction. iii) Two Keyence FD-H series clamp-on flow meters, located downstream of the sedimentation tank, to measure the outflow rate from the exit point.

4 THE PILOT SITE

The full-scale experimental setup was built at the Research Centre of the Interregional Agency for the Po River (AIPo), in Boretto, province of Reggio Emilia, Northern Italy. The centre hosts a Geotechnical and two Hydraulic modelling laboratories, covering a total area of approximately 530 m².

The area selected for the construction of the experimental system was thoroughly characterized through a comprehensive geotechnical investigation programme, including continuous-core boreholes, CPTU and laboratory tests on undisturbed and reconstituted samples. The subsoil is predominantly characterized by fine-grained materials, ranging from silts to sandy silts in the uppermost 4 m and clayey sediments in the depth interval 4-17 m; below, clean sands are encountered.

The model has a footprint of 84 m in length and 49 m in width. It consists of a reinforced earth embankment, built on a fine-grained foundation layer, overlaying a permeable sandy unit, where underseepage occurs. A general view of the full-scale model is given in Figure 5.

A poorly graded fine sand from the Padano aquifer, whose properties are summarised in Table 1, was placed and compacted using a static roller to reconstitute the aquifer. This operation ensured the homogeneity of the sample and allowed adjustment of the layers' horizontality and porosity. During compaction operations, relative density (RD) was checked through repeated sand cone tests, resulting in values between 50% and 65%. This density range was adopted as a target to replicate field conditions documented in several sections of the Po river embankments where piping phenomena have been observed. A compacted clayey blanket, whose main geotechnical properties are listed in Table 1, was subsequently placed above the sandy unit to simulate the presence of a thin fine-grained top layer. The blanket was locally thickened near the embankment toe to counteract uplift pressures. A PVC pipe with an internal diameter of 100 mm was vertically embedded through the full thickness of the blanket during the construction process, to reproduce a realistic outlet condition at the downstream side of the embankment. On the upstream side, an artificial reservoir, made of reinforced earth embankments is used to impose incremental water levels.

Table 1. Geotechnical properties of the materials used for the construction of the full-scale experimental setup.

Parameter	Unit	Aquifer	Blanket
$\gamma_{d,min}$	kN/m^3	13.7	-
$\gamma_{d,max}$	kN/m^3	16.2	-
G_s	-	2.68	2.62
D_{50}	mm	0.34	0.0015
k_{sat}	m/s	$4.0 \cdot 10^{-4}$	$4.6 \cdot 10^{-10}$
w_L	%	-	67.6
w_P	%	-	26.4

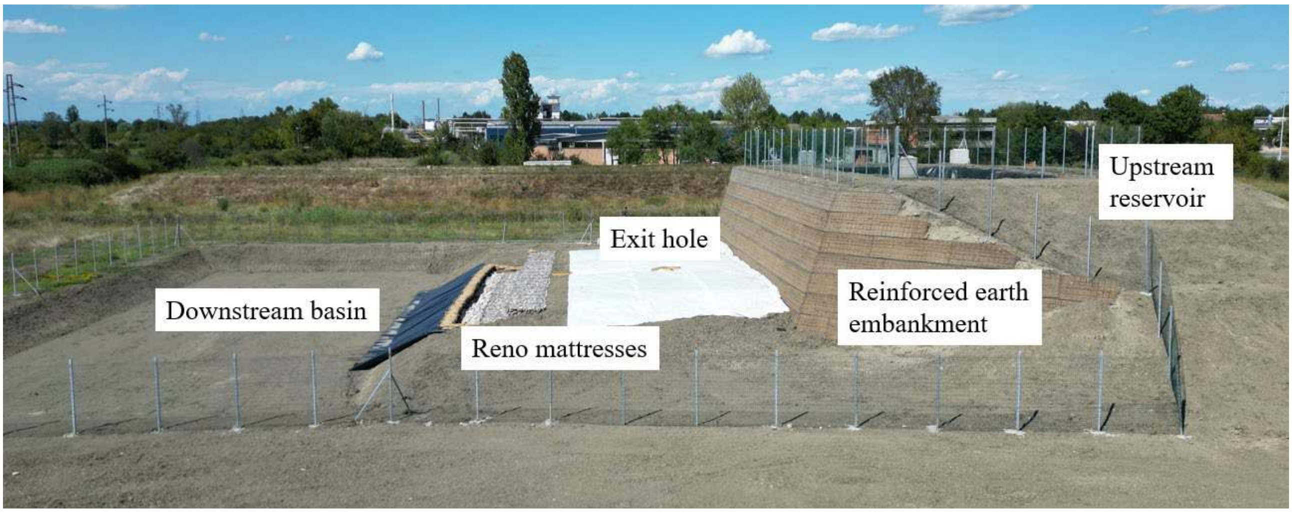

Figure 5. Lateral view of the full-scale experimental setup at the Research Centre of the Interregional Agency for the Po River (AIPo) in Boretto, Northern Italy.

The embankments have been made impermeable to ensure that water flows exclusively through the sandy layer. On the landside, gabions and Reno mattresses serve a dual purpose: they maintain a constant outflow head and allow for the collection of seepage water in a downstream retention basin.

The monitoring of pore water pressures in the aquifer relies on pore pressure transducers and on an innovative distributed pressure sensor (DPS) based on Distributed Fiber Optics (DFO) (Höttges et al., 2024). Furthermore, temperature and acoustic DFO sensors, able to monitor thermal anomalies associated with water flow and noise generated by turbulent flow within the pipes, respectively, were embedded in the aquifer, as additional strategy to track developing pipes (Figure 6). Flow meters have also been installed to quantify the outflow rate from the designated exit point and at the downstream end of the aquifer.

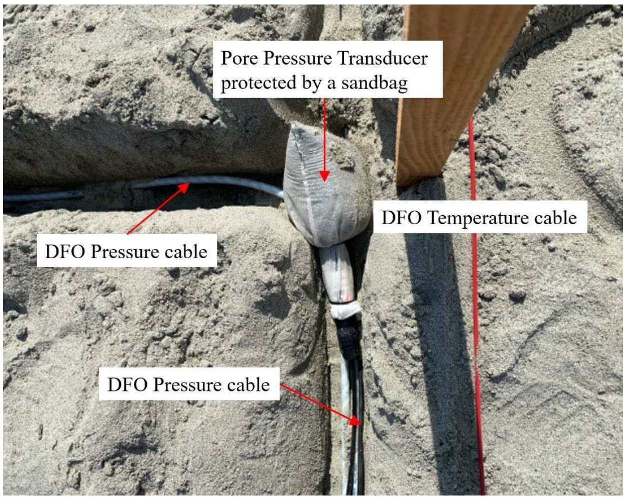

Figure 6. Detail of the monitoring system embedded within the aquifer: a pore pressure transducer and the Distributed Fibre Optic (DFO) sensors.

To further monitor the development of the erosive pipes, geophysical techniques such as Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) will be employed at the end of each erosion test.

5 OBSERVATIONS ON THE MULTI-SCALE APPROACH

The experimental programme adopts a multi-scale physical modelling strategy aimed at investigating backward erosion piping under progressively more realistic environments. The small- and medium-scale setups allow a high level of control of the hydraulic boundary conditions and model features, enabling detailed observation of pipe initiation and progression, while the full-scale facility provides the experimental benchmark to validate both the results obtained at reduced scales and the effectiveness of the proposed nature-based mitigation technology.

To ensure that the governing hydraulic mechanisms remain comparable among the three experimental setups, the grain size distribution and relative density of the soil used for the aquifer reconstruction, as well the exit configuration are kept consistent across the different scales. Data analysis is carried out using dimensionless variables, primarily the average hydraulic gradient, i_{avg}, associated with pipe initiation and attainment of the progressive stage. The latter is characterized by the pipes reaching the upstream chamber in the laboratory apparatuses or the embankment toe in the full-scale system.

The influence of scale on the critical i_{avg} for backward erosion piping has been discussed in a few studies combining laboratory and full-scale experiments (van Beek et al., 2011; Rosenbrand et al., 2022), showing that both initiation and progression depend on seepage length, leading to an overall decrease of the critical i_{avg} with increasing scale. Consequently, small-scale models may overestimate the critical head when directly extrapolated to field conditions. However, due to the limited number of full-scale experiments available in the literature, several aspects related to scale effects remain insufficiently investigated. The LIFE SandBoil pilot facility therefore provides a valuable opportunity to address these open issues under controlled conditions.

6 CONCLUDING REMARKS

This paper has presented a comprehensive multi-scale physical modelling framework developed within the European LIFE SandBoil project to investigate backward erosion piping and to assess the effectiveness of a nature-based mitigation solution. The proposed experimental approach allows the investigation of both the onset and the progression of backward erosion piping, starting from a predefined exit hole, while ensuring precise control of the hydraulic boundary conditions imposed during the tests.

The monitoring instrumentation combines different techniques to capture the evolution of the phenomenon. Pore pressure transducers embedded within the aquifer enable the quantification of head losses associated with the development of erosive channels, while flow meters detect the progressive increase in discharge as pipes widen and extend. High-resolution cameras provide detailed observation of pipe meandering processes and support the reconstruction of the volume of eroded sand. In the full-scale model, the instrumentation layout is complemented by an innovative system of distributed fibre optic sensors, capable of continuously tracking pipe development through measurements of pressure, temperature and acoustic signals.

The full-scale experimental facility constructed at the AIPo Research Centre in Boretto represents a significant step forward with respect to existing laboratory studies, bridging the gap between reduced-scale models and real embankment conditions. The full-scale facility will be employed in the coming months to conduct two dedicated tests, respectively aimed at: *i)* analysing the development of backward erosion piping in the absence of mitigation measures and *ii)* validating the effectiveness of a vertical pervious barrier in halting pipe progression. Beyond the scope of the present study, the full-scale facility is intended to remain operational as a permanent research infrastructure, supporting future experimental campaigns and international collaborations.

By providing a benchmark for design-oriented applications and numerical modelling, the proposed multi-scale physical modelling provides a robust methodological approach for identifying the key factors governing pipe initiation and progression and for validating a nature-based mitigation technology consisting of a vertical permeable barrier, with the aim of developing resilient and sustainable flood defence strategies suitable for large scale implementation.

ACKNOWLEDGEMENTS

This research has received funding from the LIFE programme of the European Union, Grant Agreement no. LIFE19 ENV/IT/000071, LIFE SandBoil.

REFERENCES

De Vries, G., Koelewijn, A.R. and Hopman, V. (2010). IJkdijk full scale underseepage erosion (piping) test: evaluation of innovative sensor technology. *Proc. 5th International Conference on Scour and Erosion*, San Francisco, USA, 649–657. https://doi.org/10.1061/41147(392)63

Dodaro, E., Tumedei, E., Marchi, M., Gottardi, G. and Tonni, L. (2024). A novel medium-scale experimental setup to investigate backward erosion piping. *Proc. 30th Meeting of the EWG-IE in Embankment Dams, Dikes and Levees and their Foundations*, Bologna, Italy.

Dodaro, E., Tumedei, E., Marchi, M., Gottardi, G. and Tonni, L. (2026). Developing a full-scale experimental set-up for the simulation of backward erosion piping. *Proc. 21st International Conference on Soil Mechanics and Geotechnical Engineering*, Vienna, Austria (accepted).

Gragnano, C.G., Camiletti, F., Forbicini, F., Gottardi, G., Marchi, M. and Tonni, L. (2023). Physical modelling of backward erosion piping for the development of nature-based mitigation strategies. *Springer Series in Geomechanics and Geoengineering*. Cham: Springer, 87–94. https://dx.doi.org/10.1007/978-3-031-34761-0_11

Höttges, A., Rabaiotti, C. and Facchini, M. (2024). A ground-breaking distributed fiber-optic pressure sensor for geohydraulic applications. *Procedia Structural Integrity*, 64, 1613–1620. https://doi.org/10.1016/j.prostr.2024.09.416

Okamura, M., Tsuyuguchi, Y., Izumi, N. and Maeda, K. (2022). Centrifuge modeling of scale effect on hydraulic gradient of backward erosion piping in uniform aquifer under river levees. *Soils and*

Foundations, 62(5), 101214. https://doi.org/10.1016/j.sandf.2022.101214

Ovalle-Villamil, W. and Sasanakul, I. (2021). Centrifuge modeling study of backward erosion piping with variable exit size. *Journal of Geotechnical and Geoenvironmental Engineering*, 147(11). https://doi.org/10.1061/(ASCE)GM.1943-5622.0002141

Ramezanifouladi, S. and Côté, J. (2024). An improved small-scale test setup for assessing backward erosion piping. *Canadian Geotechnical Journal*, 62, 1–25. https://doi.org/10.1139/cgj-2023-0279

Robbins, B.A., Montalvo-Bartolomei, A.M. and Griffiths, D.V. (2020). Analyses of backward erosion progression rates from small-scale flume experiments. *Journal of Geotechnical and Geoenvironmental Engineering*, 146(9). https://doi.org/10.1061/(ASCE)GT.1943-5606.00023 14

Rosenbrand, E., van Beek, V., Bezuijen, A., Akrami, S., Terwindt, J., Koelewijn, A. and Förster, U. (2022). Multi-scale experiments for a coarse sand barrier against backward erosion piping. *Géotechnique*, 72(3), 216–226. https://doi.org/10.1680/jgeot.20.P.174

Schmertmann, J.H. (2000). The no-filter factor of safety against piping through sands. *Proc. Geo-Congress '98*, Boston, 65–132.

Sellmeijer, J.B. and Koenders, M.A. (1991). A mathematical model for piping. *Applied Mathematical Modelling*, 15(11–12), 646–651. https://doi.org/10.1016/S0307-904X(09)81011-1

Sellmeijer, H., de la Cruz, J.L., van Beek, V.M. and Knoeff, H. (2011). Fine-tuning of the backward erosion piping model through small-scale, medium-scale and IJkdijk experiments. *European Journal of Environmental and Civil Engineering*, 15(8), 1139-1154. https://doi.org/10.1080/19648189.2011.969331 8

Semmens, S.N. and Zhou, W. (2019). Evaluation of environmental predictors for sand boil formation: Rhine–Meuse delta, Netherlands. *Environmental Earth Sciences*, 78, 457. https://doi.org/10.1007/s12665-019-8443-7

Tonni, L., Marchi, M., Bassi, A. and Rosso, A. (2024). A sand boil database for piping risk management in the Po River, Italy. *Water*, 16(10), 1384. https://doi.org/10.3390/w16101384

U.S. Army Corps of Engineers (USACE) (2000). *Engineering and design – control of piping under dams and levees*. Engineer Manual EM 1110-2-1901. Washington, DC.

Van Beek, V.M., Knoeff, H. and Sellmeijer, H. (2011). Observations on the process of backward erosion piping in small-, medium- and full-scale experiments. *European Journal of Environmental and Civil Engineering*, 15(8), 1115–1137. https://doi.org/10.1080/19648189.2011.9693317

Van Beek, V.M., Van Essen, H.M., Vandenboer, K. and Bezuijen, A. (2015). Developments in modelling of backward erosion piping. *Géotechnique*, 65(9), 740–754. https://doi.org/10.1680/geot.14.P.118

Van Goor, G.R. et al. (2022). Monitoring a full-scale backward erosion piping field test at Hedwigepolder. *Proc. 11th International Symposium on Field Monitoring in Geomechanics*, London, UK.

Zhang, F., Wang, C. and Wang, T. (2022). Model test on backward erosion piping under a K_0 stress state. *International Journal of Geomechanics*, 22(4), 04022015. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002326