

Developing a full-scale experimental set-up for the simulation of backward erosion piping

Elena Dodaro, Emanuele Tumedei, Ilaria Bertolini, Michela Marchi, Guido Gottardi, Laura Tonni
Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy,
elena.dodaro2@unibo.it

ABSTRACT: Backward Erosion Piping (BEP) is widely recognized as one of the most critical internal erosion mechanisms threatening river embankment stability. It typically develops during intense high-water events, with sand boils forming at the landside toe of the embankment. The process then progresses upstream, towards the river, gradually undermining the embankment integrity and ultimately leading to structural failure. This phenomenon has been observed in several sections of the main embankments along the Po River in Italy, as well as in other major water-retaining systems worldwide. This paper presents the rationale, design criteria and construction stages of a full-scale river embankment model, aimed both at analyzing the progression of BEP and assessing the effectiveness of a nature-based mitigation technology currently under development. The large-scale set-up will also serve as a robust benchmark to validate the results from small- and medium-scale physical modelling, recently carried out at the University of Bologna as part of the European project LIFE SandBoil. The experimental system, which has been recently completed, consists of a reinforced earth embankment, resting on a fine-grained foundation layer overlaying a permeable sandy unit, where underseepage occurs. Incremental water levels are imposed with an artificial impoundment on the upstream side. The monitoring system includes pore water pressure transducers and innovative distributed fibre optical sensors, to detect the development of erosive channels, as well as flow meters, to determine the outflow rate from a simulated exit point. This large-scale experimental system was built in an area within the AIPo Research Centre, in Boretto (Po river valley, Northern Italy). Prior to construction, a thorough characterization of the subsoil was conducted using both in-situ and laboratory tests.

KEYWORDS: river embankments, backward erosion piping, full-scale experimental set-up, underseepage.

1 INTRODUCTION

Internal erosion is acknowledged as one of the main causes of failure in water-retaining earth structures such as river embankments. Among the different forms of internal erosion, backward erosion piping (BEP) has been identified as one of the most critical mechanisms threatening the safety of such critical infrastructure (Foster et al., 2000). Backward erosion piping typically develops in stratigraphic settings where a permeable sandy foundation is overlain by a thin low-permeability *blanket* layer. The process generally initiates at the downstream toe of the embankment, in zones of local weakness or pre-existing soil cracks, where concentrated seepage forces exceed the intergranular resistance, causing particle detachment and formation of sand boils. A typical example of such surface manifestation along the Po river is shown in Figure 1. As a result of persistent or repeated high-water events, erosive channels gradually progress upstream, eventually forming continuous *pipes* beneath the embankment and severely undermining the stability of the earth structure. Figure 2 illustrates the stages of a backward erosion piping process.

The importance of understanding BEP is underscored by several historical failures, including the catastrophic dike breaches during the 1953 North Sea Flood, in the Netherlands (Sellmeijer, 1988) and along the Mississippi River in the United States, where sand boils were frequently observed as precursors to backward erosion piping-induced breaches (USACE, 2019). In Italy, over the last decades more than 130 sections along the mid-lower stretch of the Po river have exhibited sand boils reactivations, indicative of backward erosion piping during high-water events, thus highlighting the widespread and recurring nature of this internal erosion mechanism (Tonni et al., 2024).

Small- and medium-scale physical models have been instrumental in exploring the mechanisms of BEP under controlled laboratory conditions. Early experiments led to the development of the Sellmeijer approach (Sellmeijer and Koenders, 1991), a semi-empirical framework still widely used in engineering practice. Subsequent laboratory-scale investigations have provided valuable insights into hydraulic

gradients required for initiation, channel formation, and attainment of critical conditions (e.g., Schmertmann, 2000; van Beek, 2015; Ramezanifouladi and Côté, 2024). Centrifuge modelling (Ovalle-Villamil & Sasanakul, 2021; Okamura et al., 2022) and flume tests conducted in the United States (Robbins et al., 2020) have contributed to a better understanding of the role of seepage length and exit-geometry conditions in the dynamics of backward erosion piping.

In contrast to the extensive number of small- and medium-scale experiments, full-scale investigations on river embankments subjected to piping remain comparatively rare. Only a few studies have been reported in the literature, despite their unique potential to replicate realistic seepage paths, stress conditions and hydraulic gradients. In the United States, large-scale field tests and post-failure investigations along the Mississippi River system have further highlighted the vulnerability of levees to piping (USACE, 2000). Other notable examples include the full-scale experiments performed at the IJkdijk site in the Netherlands, where embankments were intentionally brought to failure by underseepage erosion (de Vries et al., 2010), and the more recent large-scale set-up in the Hedwigepolder, also in the Netherlands, which investigated the resistance of tidal sand to piping using an advanced monitoring system and post-test excavation to track pipe formation (van Goor et al., 2022).



Figure 1. A sand boil documented along the banks of the Po River, ringed with sandbags as an emergency countermeasure.

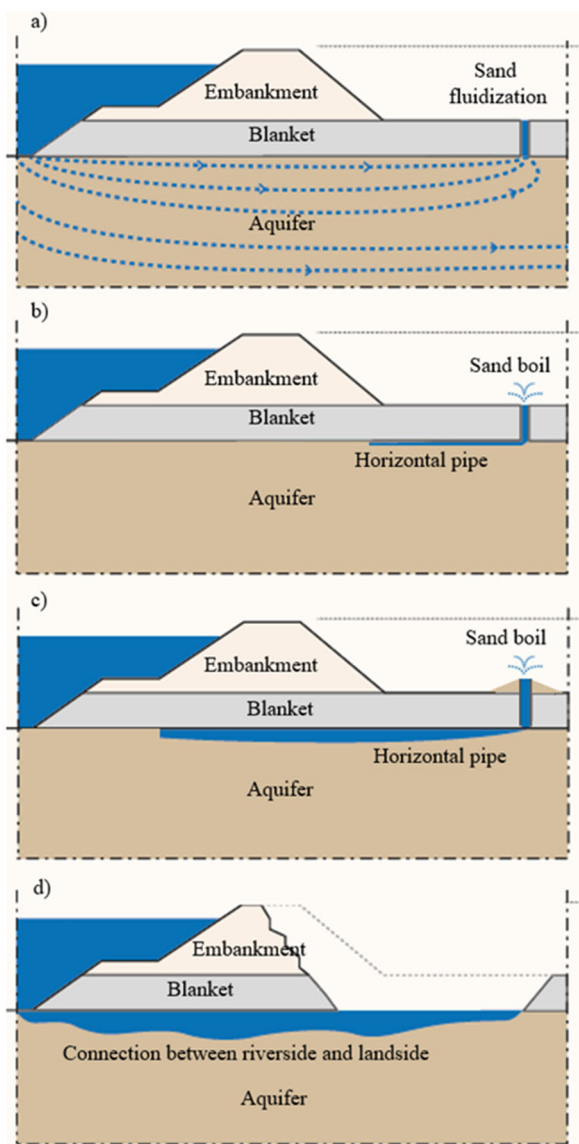


Figure 2. Schematic illustration of the backward erosion piping phenomenon: a) sand fluidization around the exit hole; b) onset of backward erosion; c) development and progression of a horizontal pipe beneath the river embankment; d) enlargement of the pipe, ultimately leading to failure.

These experiments have provided invaluable insights into the onset and development of BEP, as well as early-warning indicators such as pore pressure evolution, deformation patterns and turbidity of seepage water. In spite of their importance, however, such facilities require significant financial and logistical resources and therefore remain limited in number.

This paper presents the features and construction phases of a new full-scale experimental embankment facility developed within the framework of the European LIFE SandBoil project (<https://lifesandboil.eu/>). The experimental set-up, recently completed, is specifically intended to investigate the progression of BEP under controlled boundary conditions and to assess the effectiveness of vertical pervious barriers as a mitigation measure against this phenomenon. The facility allows control of hydraulic loading and integrates advanced monitoring systems, including pore pressure transducers, fibre optic sensors, and flow-rate measurement devices, to capture the development of erosion channels in real time, as the process evolves. In addition to providing a robust benchmark for validating small- and medium-scale models, this large-scale

set-up will also contribute to the broader effort of the European community to enhance the resilience of flood embankments under extreme hydraulic loading.

2 THE EXPERIMENTAL SET-UP

2.1 Pilot site and preliminary investigations

The full-scale experimental facility was established at the Research Centre of the Interregional Agency for the Po River (AIPo), in Boretto, province of Reggio Emilia, Northern Italy. The centre, which hosts a Geotechnical and two Hydraulic modelling laboratories, was selected as the pilot site of the LIFE SandBoil project as it offers a dedicated research environment, equipped with the logistical space and facilities needed for large-scale experiments. Although the centre itself is not located directly on a riverbank, it is close to a segment of the Po river where recurrent sand boils and piping phenomena have been historically documented.

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. Figure 3a shows piezocone profiles of a representative test pushed to a depth of 20 m, along with the corresponding classification results in terms of the well-known Soil Behaviour Type (SBT) Index, I_c .

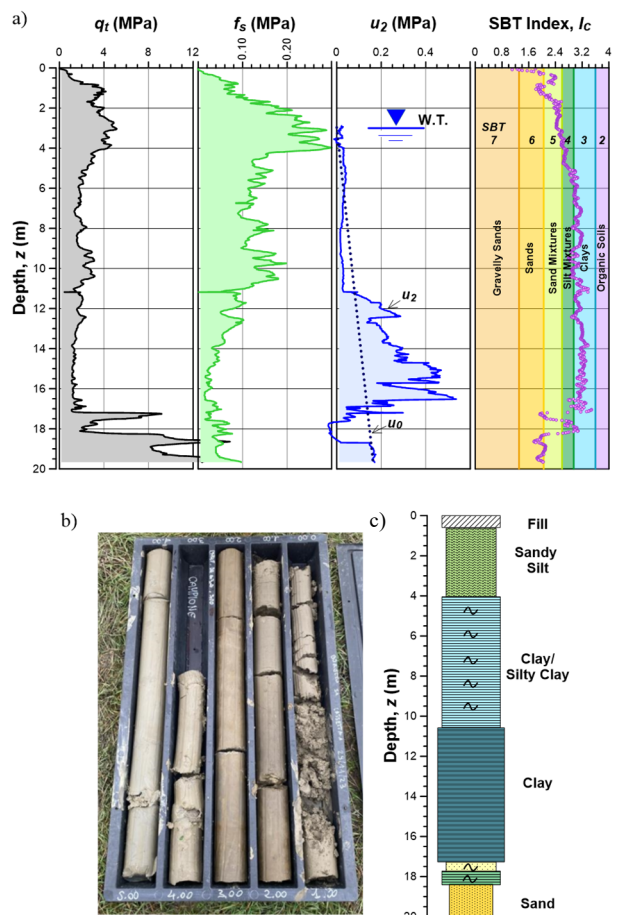


Figure 3. a) Profiles from a CPTU test carried out in the area designated for the construction of the experimental set-up, along with classification results in terms of the Soil Behaviour Type (SBT) index I_c ; b) Storage box containing soil samples from the upper 5 m, retrieved through continuous coring; c) Stratigraphic profile of the full depth investigated.

As also confirmed by an adjacent borehole (Figure 3b), the subsoil appears to be dominated by fine-grained deposits, ranging from silts to sandy silts in the uppermost 4 m and predominantly clayey sediments in the depth interval 4-17 m. Below, clean sands are encountered. Laboratory tests provided complementary data on permeability, shear strength and compressibility, supporting the hydro-mechanical characterization of the foundation soils.

2.2 Materials and construction stages

The LIFE SandBoil full-scale experimental set-up, schematically illustrated in Figure 4, covers a footprint of approximately 84 m in length and 50 m in width. The facility was designed to reproduce the boundary conditions that typically promote backward erosion piping in river embankments. It consists of a reinforced earth embankment, 6 m high, resting on a fine-grained layer which in turn overlies an artificial sandy aquifer, where underseepage is expected to occur. To recreate the artificial aquifer, a volume of $24 \text{ m} \times 14 \text{ m} \times 3 \text{ m}$ was excavated in the shallow silty layer. The removed material was reused for the construction of the embankments and ancillary components of the facility, combining efficiency with environmental sustainability. Before placing the sand, the bottom of the excavation was hydraulically isolated from the surrounding natural soil by means of an impermeable HDPE geomembrane. Subsequently, a poorly graded fine sand from the Padano aquifer, whose characteristics are reported in Table 1, was deposited and compacted using a static roller. This operation ensured the homogeneity of the sample and allowed adjustment of the layers' horizontality and porosity. During construction, relative density (D_R) was controlled 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, as commonly found in the stratigraphy beneath river segments prone to piping. This layer 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. This configuration provides a controlled preferential flow path, simulating the presence of a localized crack and thereby promoting the onset of piping phenomena.

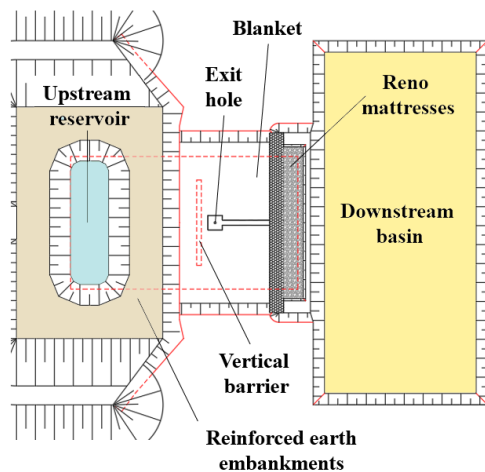


Figure 4. Plan view of the experimental facility in Boretto (Italy).

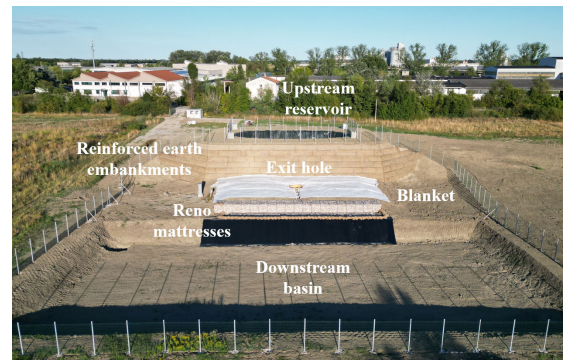


Figure 5. Aerial view of the experimental system at the end of construction, with a close-up of the downstream basin.

The seepage path from the upstream embankment to the vertical pipe has a length of 11.25 m. Under these conditions, the maximum global hydraulic gradient acting towards the pipe is approximately 0.5, thus fully consistent with field values observed in river embankments affected by backward erosion piping.

Furthermore, an upstream reservoir, hydraulically connected at its base to the sandy layer, was built using reinforced earth embankments. With a capacity of at least 400 m^3 , the reservoir allows for the application of incremental water levels in a controlled manner. To ensure that water flow is confined to the sandy layer, the inner banks were made impermeable. On the landside, a downstream basin was constructed using gabions and Reno mattresses. This additional element serves the twofold function of maintaining a constant water level and enabling collection, measurement, and regulation of seepage water exiting the aquifer. Figure 5 shows an aerial drone image of the complete experimental system at the end of its construction, captured from the downstream basin perspective.

Table 1. Geotechnical properties of the blanket and aquifer layers of the full-scale experimental set-up.

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

2.3 Monitoring system

A comprehensive monitoring system was designed and implemented to capture pore pressure and flow rate variations, which have proven effective in identifying the propagation of erosion channels, as demonstrated in previous laboratory experiments on small- and medium-scale models (e.g., Gagnano et al., 2023; Dodaro et al., 2024). The instrumentation embedded within the sandy layer consists of both conventional pressure transducers and an innovative Distributed Pressure Sensor (DPS), based on Distributed Fibre Optic (DFO) technology (Höttges et al., 2024), as shown in Figure 6. A total of 16 piezometers were installed: 10 units with a full-scale range of 1 bar, 5 with a full-scale range of 0.4 bar, and 1 with a full-scale range of 0.6 bar. These sensors exhibit a response time of less than 1 ms for pressure changes between 10–90% of the full-scale values, and an operating temperature range between $-5 \text{ }^\circ\text{C}$ and $80 \text{ }^\circ\text{C}$. To ensure proper saturation and protect the sensor, each piezometer was enclosed in a permeable sandbag prior to installation.

The DPS provides continuous distributed measurements of pore pressure along the fibre. The system operates within a pressure range of 0–200 kPa and offers an accuracy of $\pm 5\%$ of the readings. Depending on the acquisition unit employed, it achieves a pressure resolution of 0.1 kPa, with acquisition times ranging from 5 to 10 s. The fibre consists of multiple sensing elements arranged in a helical configuration within a gel-filled protective sheath, reinforced with aramid fibres to ensure tensile strength. As an integrative strategy for tracking erosive channels, additional DFO-based sensors for temperature and acoustic monitoring were embedded in the aquifer. The Distributed Temperature Sensor (DTS) enables the detection of thermal anomalies associated with water flow variations, operating over a temperature range of 0–85 °C with an accuracy of 0.1 °C. Passive measurements allow monitoring of natural thermal variations, while the active ‘heat pulse’ method enables the identification of piping by analyzing the cooling rate of the heated fibre (Bersan et al., 2018). The Distributed Acoustic Sensor (DAS) complements the system by detecting noise generated by turbulent flow within the erosion pipes, with acquisition frequencies up to 400 Hz. Its robust configuration, including aramid filling and a protective sheath, ensures durability under field conditions.

To further monitor the development of the erosive channels, geophysical techniques such as Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) will be employed at the end of each erosion test, following previous experiences reported in a few studies (e.g., Bernatek-Jakiel & Kondracka, 2016). In addition, flow meters will be installed to quantify discharge both at the outlet point created in the blanket and at the downstream end of the facility, where the excess water is collected in a basin of known geometry.

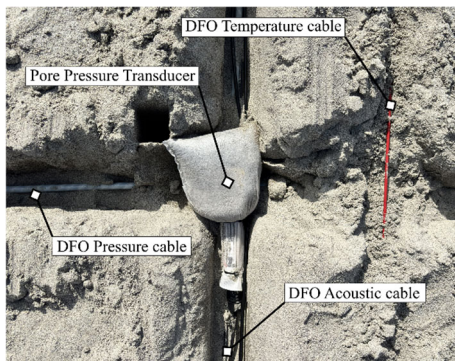


Figure 6. Detail of a pore pressure transducer protected by a sandbag and Distributed Fibre Optic (DFO) sensors.

3 CONCLUDING REMARKS

This paper has presented the design features of a full-scale experimental facility developed within the framework of the LIFE SandBoil project, to investigate backward erosion piping under realistic boundary conditions. The facility, located at the AIPo Research Centre in Boretto (Italy), was conceived to bridge the existing gap between small-scale laboratory models and the very limited number of full-scale studies available in the literature. The experimental set-up will be employed in the coming months to conduct two tests, respectively devoted to: *i*) analyse the development of pipes in the absence of mitigation measures, and *ii*) validate the effectiveness of a vertical pervious barrier in halting the progression of backward erosion piping. Beyond these initial campaigns, the facility is expected to remain operational as a permanent large-scale research infrastructure, supporting future investigations and collaborations with national and international research institutions. By providing a benchmark for numerical modelling

and laboratory investigations, the full-scale facility has the potential to significantly advance the understanding of river embankment vulnerability to underseepage and to contribute to the development of innovative, nature-based mitigation technologies for flood risk management.

4 ACKNOWLEDGEMENTS

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

5 REFERENCES

- Bernatek-Jakiel, A. and Kondracka, M., 2016. Combining geomorphological mapping and near surface geophysics (GPR and ERT) to study piping systems. *Geomorphology* 274, 193-209.
- Bersan, S., Koelewijn, A.R. and Simonini, P., 2017. Effectiveness of distributed temperature measurements for early detection of piping in river embankments. *Hydrology and Earth System Sciences Discussions* 21, 6611-6626.
- 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, United States, 649-657.
- Dodaro, E., Tumedei, E., Marchi, M., Gottardi G., Tonni, L., 2024. A novel medium-scale experimental setup to investigate backward erosion piping. *Proc. 30th Meeting of the European Working Group on Internal Erosion in Embankment Dams, Dikes and Levees and their Foundations*, Bologna, Italy.
- Foster, M., Fell, R. and Spannagle, M., 2000. The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal* 37(5), 1000-1024.
- Gragnano, C.G., Camiletti, F., Forbicini, F., Gottardi, G., Marchi, M., Tonni, L., 2023. Physical modelling of backward erosion piping for the development of natural-based mitigation strategies. In: A. Ferrari, et al., eds. *Geotechnical Engineering in the Digital and Technological Innovation Era*. Springer Series in Geomechanics and Geoengineering. Cham: Springer, 87-94.
- 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.
- Okamura, M., Tsuyuguchi, Y., Izumi, N., 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), 1012-14.
- 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), 04021114.
- Ramezanifouladi, S. and Côté, J., 2025. An improved small-scale test setup for assessing backward erosion piping. *Canadian Geotechnical Journal* 62, 1-25.
- 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), 04020093.
- Schmertmann, J.H., 2000. The no-filter factor of safety against piping through sands. *Proc. Judgment and Innovation. 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.
- Tonni, L., Marchi, M., Bassi, A., Rosso, A., 2024. A sand boil database for piping risk management in the Po River, Italy. *Water* 16(10), 1384.
- 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: USACE.
- 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.
- 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.