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Probability of Reactivation of a Sand Boil near a River Embankment of the Po River (Italy)

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Abstract: This paper presents a reliability analysis referred to backward erosion piping phenomena. The study is carried out on a cross-section of the major Italian watercourse, the Po River, where evidence of piping effects, namely a sand boil of remarkable size, has been periodically detected during past high-water events.The initiation of the process has been analysed by means of a two-dimensional (2D) finite element (FE) model of the groundwater flow beneath the river embankment, to obtain an effective description of the hydraulic gradient variationclose to the sand boil due to the rise of the river water level, and thus capture the conditions triggering piping.Detailed stratigraphic soil profiling, as well as careful geotechnical characterization of the riverbank sediments and the foundation subsoil, have been carried out. In particular, representative mean values of the saturated permeability, and the relevant standard deviation, have been obtained from statistical analysis of the estimates provided by empirical correlations applied to cone penetration tests (CPT) profiles.The methodology adopted for reliability analysis relies on the use of fragility curves. The probability of backward erosion piping initiation as a function of the floodwater elevation has been therefore calculated assuming that hydraulic conductivity and a few geometrical parameters affecting the problem could be considered as random variables in the FE model. Then, the probability of reactivation has been estimated using the Taylor's Series first-order second moment (FOSM) method. The same procedure has been developed by applying thewell-known blanket theory. Both analyses result in a high probability of reactivation of the sand boil, also for moderate river levels. In addition, fragility curves have been interpreted in the light of the available field observations. The interpretation indicates that, despite the significant variability of the water levels recorded at the on-set of reactivations, the blanket theory tends to overestimate the probability of sand boil initiation, while the FE analysis resultsare closer to the field observations collected in the last 20 years.

Keywords: River embankments; backward erosion piping; probabilistic analysis;fragility curves; Po river.

1 The case study

The Po River, 652 km long, is the major Italian watercourse and flows through the most densely populated and economically developed area in the country. It is bordered for about half its length by a system of major embankments, whose stability is undoubtedly a major concern.Based on field evidence (Marchi et al.2021) and results from a large-scaleflood risk assessment project (Gottardi et al. 2015) involving about a hundred relevant sections over 90 km, the backward erosion piping mechanism has been identified as a major threat to the safety of the Po river embankments. This process, which is typically revealed on the ground surface by the presence of the so-called sand boils, consists in the development of shallow channels or"pipes" in a sandy aquifer beneath a river embankment, as a consequence of the progressive erosion and transport of soil particles due to under seepage pressure. Initiation of soil erosion occurs landside, where a free unfiltered surface or a ground crack exists and the resulting upward seepage pressures may locally trigger sand fluidisation, but the progression and widening of the pipes towards the source of the seepage may eventually result in a collapse of the river embankment, with catastrophic consequences (Van Beek et al 2013).

This paper presents a reliability analysis carried out on a section of the Po river embankments in Guarda Ferrarese (northern Italy), province of Ferrara (see Figure 1 left), where a large natural sand boil periodically reactivates (see photos A and B on the right side in Figure 1). The cross-section A-A in Figure 1 has been investigated by means of geotechnical in situ tests, such as boreholes and piezocone tests (CPTU), which provided the stratigraphic architecture shown in Figure 2 on top. The local soil profile consists of a confined aquifer (unit A), about 10-15 m thick, in which the main groundwater flow concentrates and the erosion process occurs. The blanket, which overliesthe aquifer, is composed ofunit B (alternation of silty mixtures) and unit C (clays and silty clays). In the area where the blanket thickness tends to decrease, the "vertical pipe" (exit hole) was created by the water flow during the first sand boil activation. Although re-filled by the sand transported by the water during the boiling phase, such discontinuity has remained after this first eventand is very likely to have enlarged during the subsequent events, thus creating a permanent connection between the aquifer and the ground surface.

Below the aquifer, an alternation of predominantly fine-grained soil layers (clays and silty clays, but also silty mixtures) has been detected. Physical characterization of the deposits has been carried out by means of laboratory tests on disturbed and undisturbed soil samples, while mechanical and hydraulic properties have been determinedthrough CPTU tests (also including dissipations) and Lefranc tests (Bertolini et al. 2022).

Figure 1(Left)Aerial photo of the investigated section along Po River with a schematic map of the watercourse; (Right)Sand volcanos and sack ring during the high flood event in November 2014.

Fragility curves have been calculated in order to evaluate the probability of backward erosion piping initiation, as a function of the river water level, also taking into account the inherent variability of hydraulic soil properties. To this purpose, two methods have been applied. Firstly,a fully coupled saturated flow 2D finite element model has been developed and series of analyses have been carried out to simulate seepage under the river embankment. Then, an analytical study was carried out on the base of the blanket theory.

2 The 2D numerical model of the groundwater flow

The2D finite element (FE) model of the groundwater flow beneath the investigated river embankment has been developed with the aim of calculating the pore pressure distribution around the exit hole of the sand boil, as a function of incremental changes in water head (H) governed by the river level. The numerical model is 63 m highand433m long, thusany potential boundary effect on the simulated groundwater flow is prevented. Figure 2 (bottom) shows the discretized model (7667 triangular elements,61763 nodes) generated by the code Plaxis2D.Following García Martínez et al. (2020a), the exit volume is modelled as a cylindrical vertical exit pipe witha hemispheric cluster at its base (see the enlarged detail of Figure 2,on top).The hemisphere is meant to simulate the presence of a previously eroded soil volume, characterized by a permeability higher than thatof the aquifer.

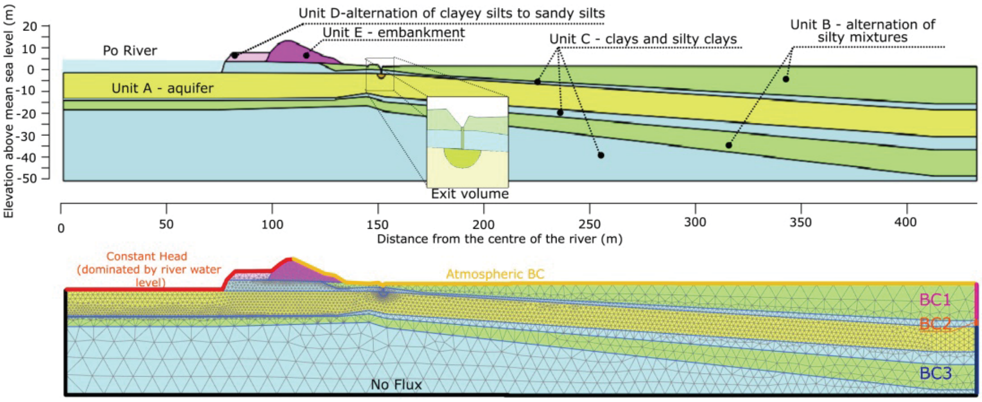


Figure 2.(Top):Soil stratigraphy of the investigated river embankment section, as reproduced in the numerical model.**(**Bottom):discretized model of the river embankment section with indication of the hydraulic boundary conditions.

As shown in Figure 2, the bottom of the model is located within a clayey layer (deep Unit C) not involved in the underseepage causing the erosion process; therefore a no flux boundary condition (BC)is assigned. The left vertical boundary of the model is a no-flux boundary as well, since it corresponds to the centreline of the river.Underseepage within the aquifer is governed by the water level in the river, hence the constant head applied to the interface between the river and Unit A.The same condition also applies to the inner slope of the river embankment. In particular, a ramp of no. 15 steady state stages of constant hydraulic head has been applied in the analyses, in order to simulate a variation in the water level from 0 m (the river bed) to 15 m (crest of the river embankment).

The hydraulic boundary conditions adopted on the right-side of the model are meant to reflect some field evidences revealed by a few piezometers, recently installed landside at different distances from the river embankment (close to the toe, in proximity to the sand boil and about 300 m from the bank).Accordingly, a constant hydraulic head (BC1 in Fig.2) is applied to shallow Unit B, where the pore water pressure regime is governed by a phreatic surface and water table oscillations depend on rainfall and evapotranspiration; a different value of the hydraulic head (BC3), depending on oscillations of the river water level, is instead applied to the aquifer (and the underlying soil layers). Finally, a linear variation of the hydraulic head (BC2) is applied to the interbedded fine-grained Unit C, thus accounting for the seepage pressure induced by the presence of two different piezometric levels.

3 Construction of the fragility curves

The use of fragility curves in flood risk assessment and management was first proposed by the U.S. Army Corps of Engineers (USACE) in 1991. Since then, an ever-increasing number of engineering studies and research projects have developed and applied the concept of fragility curve to describe the performance of river embankments or for its integration into strategic and operational flood management systems, as detailed in Schultz et al. (2010), among others. As known, fragility curves are functions that describe the probability of failure with respect to a load to which a system might be exposed. In this study, the term “failure” indicates a sand boil reactivation (i.e. the critical hydraulic gradient in the vertical pipe is reached or exceeded), while the term “load”corresponds to the floodwater elevation.In this paper, the FOSM (first-order second moment) analytical solution(e.g. USACE, 1999) has been adopted to calculate the probability of activation, while the performance of the river embankment section, with respect to underseepage phenomena,has been investigated using both the numerical approach mentioned above andthe well-established blanket theory, the latter based on closed-form equations. Information on the variability of geotechnical parameters and geometrical characteristicshas been acquired from site investigations.

3.1 Underseepage Analysis through the numerical model

The numerical modelshownin Section 2has been adopted for simulating underseepage in the investigated section.The geometry of the soil layers, defined from interpretation of a large number of boreholes and CPTU tests,has been assumed to be deterministic.At the same time, five random variables have been considered:

- the permeability of soil units A,B and C (k_A,k_B and k_C, respectively) (Figure 2 on top);
- the diameter of the existing vertical exit hole (d_{exit}), hereafter referred to as the “verticalpipe”;
- the permeability of the exit volume(k_{exit}).

A summary of the mean values of these random variables and their standard deviations is reported in the first column of Table 1. As regards the vertical pipe diameter (d_{exit}), the values shown in Table 1 have been derived from field measurements carried out on the investigated sand boil during the 2018 reactivation.In this occasion,d_{exit}turned out to vary in the vertical direction between 0.20 m, at the verticalpipe base, and 0.35 m at its top (Marchi et al 2021). A minimum diameter equal to 0.1 m has been also supposed, in order to include a possible initial condition that may have characterized the beginning of the reactivation, not investigated during field measurements. On the contrary, the radius of the hemispheric cluster of the exit volume has been assumed to be a deterministic variable, equal to 2 m.A calibration study proposed by García Martínez et al (2020b) showed indeed that this radius value allows to correctly predict reactivations observed during past high-water events.As described in Garcia Martinez et al. (2020a), the permeability of the exit volume(k_{exit}) has been deduced from the Darcy law, according to the following expression:

$$k_{exit} = \frac{v_0 n^{\alpha}}{i_c} = \frac{\rho_s v_0 n^{\alpha}}{(\rho_s - \rho_w)(1-n)} \tag{1}$$

where i_c is the Terzaghi (1960)’s critical hydraulic gradient, equal to 0.91, v_0 is the settling velocity of the spherical particles (equal to 3.6 cm/s from the Stockes’ law), n is the porosity of the sand bed immediately before fluidization, α (=4.27) is an empirical exponent that can be deduced from the grain size distribution(in particular from d_{50}, according to Baldock et al. 2004),ρ_s is the sand particle density (=2650 kg/m^3) and ρ_w is the water density. Then, the variability of k_{exit} has been obtained by varying the porosity (n)between the in situ value estimated for Unit A,and its maximum possible value (n_{max}), corresponding to the loosest condition. In particular, SPT-based estimates of the relative density of the aquifer have been used to calculate the in situ value of n, whereas n_{max} (together with n_{min}) has beenobtained according to empirical correlations proposed by Cubrinovski and Ishihara (1999, 2002).

The saturated permeability has been obtained from CPTUtests, using well-known empirical correlations (Robertson and Cabal, 2010) which express$k$ as exponentiation of 10 by a function of the soil behaviour index I_c.The series of values predicted for the different soil units have been first interpreted in terms of $\log_{10} k$. For

Unit A, Unit C and Unit D a normal distribution has been observed, thus implying that the saturated hydraulic conductivity *k*is a log-normally distributed variable. This outcome confirms what observed in a number of published studies (e.g. Sudicky 1986), irrespective of the soil classes taken into account. Accordingly, a simple logarithm base change from 10 to the Euler's number has been carried out to apply the properties of the log-normal distribution. Only permeability of Unit B has been found to exhibit a bi-modal distribution, likely due to the high heterogeneity of this soil layer, which is basically a silt mixture with a variable content of sand and clay (Bertolini et al. 2022).Despite this, a Gaussian distribution has been eventually adopted also for Unit B, being the meanvalue of the $\log_{10}k_B$distribution between the two main peaks, one corresponding to a clayey-silt and the other to a sandy-silt.

Table 1. Mean values of the input data for the probabilistic safety assessments using the FE numerical 2D modeland the USACE blanket theory(standard deviation is given in square brackets).

FE MODEL	USACE APPROACH		
Probabilistic variables	Deterministic variables	Probabilistic variables	
k_A (m/s)=1.46E-05 [1.17E-05]	x_1 (m)= 20.5	d(m)=10.07 [1.38]	k_A (m/s)=1.46E-05[1.17E-05]
k_B (m/s)= 5.35E-06 [1.04E-06]	L_2 (m)= 36.2	zc (m)=1.52 [0.29]	k_B (m/s)= 5.35E-06[1.04E-06]
k_C (m/s)= 2.39E-08 [4.66E-09]	L_3 (m)= ∞	zb (m)=1.89 [0.12]	k_C (m/s)= 2.39E-08[4.66E-09]
k_{exit} (m/s)=0.00162 [0.0007]	x (m)= 17.6	k_A/k_C =608.9 [503.6]	z_{eq} (m)=1.53[0.29]
d_{exit} (m)=0.225 [0.125]			

The assessment of the safety (factor of safety) of the river embankment section with respect to the reactivation of the sand boil was then achieved by comparing the critical hydraulic gradient and the average gradient in the vertical pipe, as deduced from the numerical model. A total of 11 simulations have been run. In the first simulation, the mean values (μ) have been adopted for the whole set of random variables; in the other simulations, only one variable at a time has been set to the mean value (μ) ± the standard deviation (SD), while assuming all the other variables equal to their mean value.

Results from the FE numerical simulations are shown in Figure 3. In particular, Graph A in Figure 3 reports the average value of the hydraulic gradient in the vertical pipe (i_{avg})as a function of the water level *H* in the river. The average gradient in the vertical pipe is calculated as the ratio between the head loss along the pipe and the depth of the pipe itself (~2.65 m).The vertical pipe depth is obtained by subtracting the depth of the ditch, in which the sand boil periodically reactivates,from the average value of the blanket thickness (3.41m). The different lines depicted in the graph refer to the different values adopted for the random variables in each simulation.

Graph 3B reports the fragility curve that describes the conditional probability of failure (i.e. condition$i_{avg}>i_{crit}$, withi_{crit}=0.91) over the full range of hydraulic loads to which the system could be exposed. This curve provides evidence that for a water height covering the waterside berm (H~ 9m), the probability of a sand boil reactivation is 53%; while for a river water height reaching the crest (H = 15m) the probability rises to 64%.By interpreting the global performance of the model, it turns out that the most significant uncertainties derive –in order - from the diameter of the vertical pipe, with a total variance of approximately 55%, from the permeability of Unit A (~37%) and from the permeability of the exit volume (~8%).

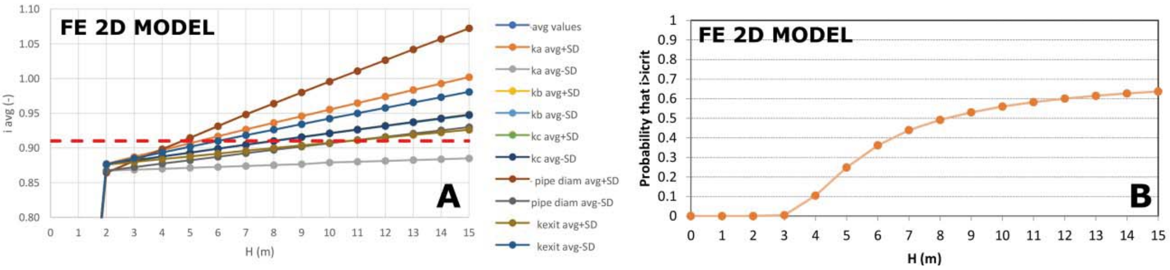


Figure 3. (A)Average hydraulic gradient in the vertical pipe, as deduced from the FE model,vs incremental water level in the river; (B)Cumulative probability of failure (fragility curve).

It is important to highlight that the observed water level in the river which triggered reactivations in the past vary between 7.5 and 9.5 m, which corresponds in this analysis to a probability of failure equal to 47-54%. The major flood event dates back to 2000, and no reactivations were recorded in this cross-section before 2014. Technicians of the Interregional Agency for the Po river basin (AIPo) report that the first activation of this sand boil was recorded after installation of a pipeline not far from the current sand boil location. During the excavation works the use of well points seemed to have cause removal of sand from the substratum. Such event is very likely to have locally aggravated the susceptibility of the river embankment system to backward erosion piping.

3.2 Underseepage analysis with the blanket method

The classical method of under seepage analysis, known as “Blanket Theory” (e.g. USACE1999),allows predicting when a sand boil formation (i.e. “a first time sand boil”) is likely to occur. The applicability limit of the method, which enables to get a reliable estimation of the hydraulic exit gradient, is that the coefficient of permeability of the blanket must be 10 (or more) times lower than that of the aquifer. Figure 4A reports the simplified geometry of the investigated section with the main variables of the problem. Note that in this scheme, the semi-pervious top stratum is characterized by a uniform thickness, both riverside and landside. The Factor of Safety (FOS) against boilingor heavingis the ratio between the exit gradient (i_{exit}) at the toe of the levee and the critical gradient (i_{crit}). The exit gradient is a function of a number of variables, such as the thickness of the aquifer and of the blanket (“*d*” and “*z*”, respectively), the ratio between the permeability of the aquifer and that of the top stratum (k_A/k_C), the embankment base L_2 and the net residual water pressure head at the embankment toe h_o (Figure 4A). Among them,*d*, *z*, k_A/k_C have been considered as random variables and the characteristic values of their normal distribution (μ and *SD*) are summarized in Table 1. The intervals of variation of the aquifer and blanket thickness (*d* and *z*, respectively) have been investigated by means of CPTU stratigraphic logs at different distances from the river. Due to the fact that the blanket stratum of the section is formed by two layers, one belonging to Unit C (thickness z_c) and one to Unit B (thickness z_B), an equivalent thickness of the blanket (z_{eq}) has been defined according to the following equation, as suggested in USACE (1999):

$$z_{eq} = z_c + \left(\frac{k_c}{k_B}\right) * z_B \tag{2}$$

The resulting equivalent thickness decreases from 3.41m (z_C+z_B) to 1.53m, with a significant impact on results in terms of probability of failure.The seepage length, given by the sum of x_1+L_2+x (see Table 1), has been defined as a deterministic variable. Figure 4B shows the cumulative probability of failure that results from the application of the Taylor’s series method (FOSM), assuming two different critical hydraulic gradients, 0.85 as suggested by USACE (1999) and 0.91 as found using Terzaghi (1960).

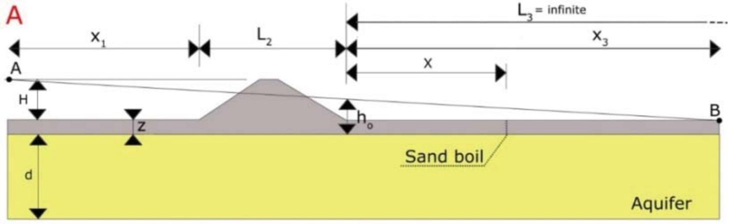
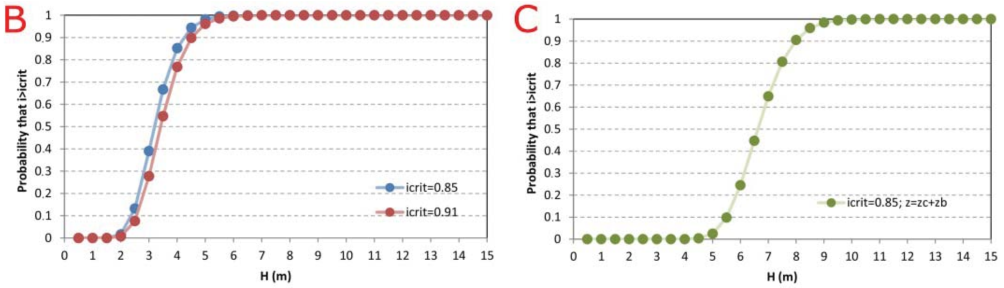


Figure 4.(A).Scheme of a BEP phenomenon affecting the investigated river embankment characterized by a semi-pervious top stratum of uniform thickness riverside and landside (modified from USACE, 2000). (B**)** Cumulative probability of failure (fragility curve) obtained applying the blanket theory and adopting the equivalent thickness (z_{eq}) of the blanket.(C).Fragility curve as obtained adopting the real thickness of the blanket (z_C+z_B).

It can be observed that in both cases the probability of failure is negligible until the water level in the river reaches 2m high. Then it becomes 50% for 3.1 m, reaching 100% when the water arrives at 7 m in high, this being an elevation lower than that of the riverside berm. In addition, by considering the overall performance of the model and the relative size of the variance components, it turns out that the major uncertainty is due to the blanket thickness, which provides a total variance equal to ~60%. In order to highlight the influence of this variable in the probability assessment, the case in which *z* is assumed as simple sum of z_A and z_B is shown in Figure 4C. In this case the probability of reactivation remains very low until the water head exceeds 5m;above that value it increases abruptly and approaches a probability of failure of 50% at around 6.5m. As pointed out in the previous section, no reactivations have been recorded for water levels in the river lower than 7.6 m.This



observation suggests that, in this case study, the blanket method tends to overestimate the probability of failure and therefore seems to be not particularly suitable to predict the sand boil reactivations.

4 Concluding remarks

The paper addresses the assessment of BEP initiation through a probabilistic approach, using two different methods, namely the well-establish “blanket theory” and a FE underseepage analysis. The methodologies have been applied to a riverbank section along Po River affected by periodical sand-boil reactivations during high-water events. The stratigraphy and the main physical, mechanical and hydraulic properties of the subsoil have been obtained from in situ investigations and laboratory tests. Results have been plotted in terms of fragility curves (probability of BEP initiation conditioned on the river water level), developed through the Taylor’s series method (FOSM). As expected, the fragility curves derived from the numerical FE model and from the USACE method are not directly comparable. Indeed, they rely on distinct methodological approaches that are conceptually different. In particular, both methods are extremely sensitive to the blanket thickness, which is determined using two different strategies.In the USACE approach, the blanket must be assumed as homogeneous and of constant thickness. On the contrary, in the FE model the thickness of the top stratum, riverside and landside, varies along the section, as deduced from field investigations. The results of these two different analyses have been compared to the reactivation water levels observed during recent high-water events. The comparison indicates that, despite the significant variability of field observations, the blanket theory tends to overestimate the probability of activation/reactivation, while the FE analysis results are closer to the field observations carried out in the last 20 years.Thanks to the experience provided by long-term observation on the investigated sand boil, this study can improve the confidence of practitioners in the applications of different strategies of analysis to other case studies, especially when a reduced number of information is available.

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