Numerical simulation of the groundwater flow leading to sand boil reactivation in the Po River

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Abstract: The reliability of river embankments is essential for flood risk management. The Po River, which flows through the North of Italy, is safeguarded over half of its length by major river embankments. Performance assessment of such water-retaining structures has become a major concern following some significant flood events in the past. Among the possible initiating causes of failure, backward erosion piping turns out to be particularly threating in the middle-lower stretch of the river. In particular, the November 2014 high-water event triggered the formation or reactivation of a few important sand boils. The paper presents a preliminary 3D finite element model of the groundwater flow through a selected cross section of the Po river, located in the Province of Reggio Emilia, which experienced a reactivation of piping phenomena after the 2014 event. The numerical model, based on a detailed geotechnical characterization obtained from in situ tests, was calibrated on the basis of the 2014 high-water event measurements and verified for a subsequent event that took place in November 2016, though without any relevant sand boil reactivation. Results are discussed with the aim of providing some insight into the mechanism under study.

Keywords: groundwater flow, backward erosion piping, sand boil , Po River

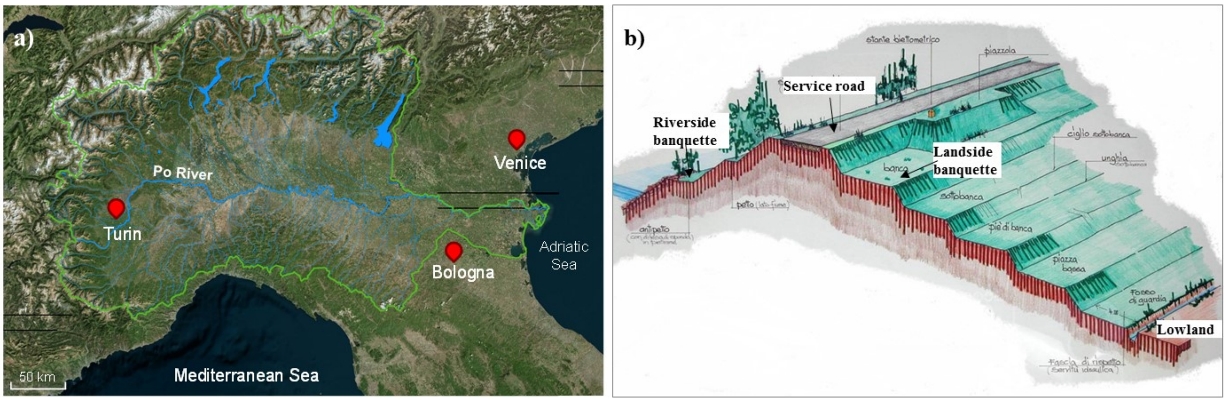

Figure 1. a) View of the Po basin ; b) Drawing of the evolution of the main embankment in the Rovigo Municipality, middle-lower portion (courtesy of AiPo).

1 INTRODUCTION

The Po River flows through the North of Italy from West to East (Figure 1a) and is the longest watercourse in the country. It is typically safeguarded by water-retaining structures existing since the 16th century. Following some significant past events, flood prevention has become a crucial concern and current river embankments (Figure 1b) have been progressively improved by enlargement of their cross section, increase of their height or enhancement of their mechanical properties. This has decreased the frequency of failure occurrence. Furthermore, such flood protection systems have been extended upstream and towards the main tributaries, thus leading to higher water levels reached during heavy rainfall events.

The Po plain is very densely populated and has a high concentration of extensive agricultural and industrial activities, hence the human and economic damages induced by a river embankment failure would be very high. The stability of such structures is therefore essential for local communities.

As can be observed in Figure 2, backward erosion piping, which involves the development of shallow channels in the sandy aquifer right below the embankment, has proven to be, after overtopping, one of the most important failure mechanisms during the last two centuries. The 2014 major high-water event has been the most relevant in the last decades. It occurred in the mid of November (from 16th to 22nd), preceded by two more moderate flood waves, and it was particularly threatening in the middle-lower stretch of the river, triggering the formation or reactivation of a few important sand boils (García Martínez et al., 2016).

The relevance of backward erosion piping phenomenon in the Po river embankments has led to new investigations and studies (promoted and coordinated by the Interregional Agency for the Po River, AiPo) being carried out in order to early detect and prevent it. In particular, a new database of the most critical areas is currently under construction. Furthermore, it is intended to develop a methodology for the definition of an alarm threshold that would correlate the river level evolution to the initiation of the phenomenon, which would be a sort of early warning system.

The term backward erosion is designated here to the mechanism by which shallow pipes are formed at the interface of the sandy aquifer and an impermeable layer, which overlies it and acts as a roof to the pipes, preventing their collapse (Bonelli, 2013). This is a typical configuration of Po river embankment sections.

The process starts when a sufficient hydraulic head difference exits across the embankment that leads to a concentration of flow lines toward a downstream unfiltered open exit, which is often due to local cracks in the impervious layer. Such concentration of groundwater flow near the exit cause higher flow velocities near it. This can lead to the formation of sand boils. When the water flow is sufficient to carry sand particles from the aquifer outside the boiling zone, deposition occurs forming what is commonly

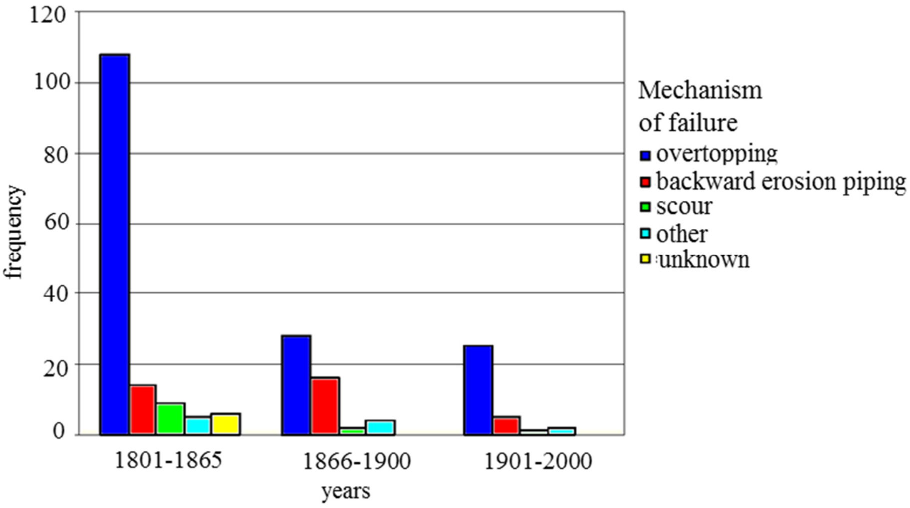

Figure 2. Number of Po river embankment failures, divided into mechanisms of collapse, during the last two centuries (modified from Autorità di bacino del fiume Po, 2005).

Figure 3. Ringed sand volcano near Boretto (Courtesy of AiPo).

known as "sand volcano" (*fontanazzi* in Italian). At this point, shallow pipes might start to develop in the aquifer (van Beek, 2015).

Sand volcanoes are often observed on the land side of Po river embankment sections during high-water events. A countermeasure that is typically implemented is ringing them with sand sacks in order to reduce hydraulic gradients and stop sand transport. Figure 3 shows a ringed sand volcano during the 2014 high-water event near Boretto, in the Province of Reggio Emilia.

In particular, this paper describes the reactivation of a sand boil (Fig. 3) along a river embankment cross section in the Province of Reggio Emilia. Detailed stratigraphic profile and geotechnical characterization of the river embankment foundation system have been based on in situ testing. Then, a preliminary 3D finite element model is presented, aimed at reproducing the groundwater flow which led to sand boil reactivation. The model has been calibrated on the basis of the 2014 high-water event measurements and then verified for a subsequent event that took place in November 2016, during which sand boil reactivation did not occur.

2 THE CASE STUDY

In the case of study presented in this paper, a cross section located in the province of Reggio Emilia and affected by a recently reactivated sand boil has been analysed. In particular, the last reactivation occurred during the November 2014 high-water event, when sand transport was observed in the morning of the 15th.

2.1 Geotechnical characterization

The geotechnical properties of the subsoil have been defined according to the information provided by a number of situ tests carried out along the selected cross-section. In particular, a set of three piezocone tests (CPTU), located in the floodplain area, on the bank crest and at the toe of the bank, respectively, has been used. Such tests were carried out within a major project funded by the Italian Government for assessing the seismic stability of about 90 km of Po river embankments in the middle-lower stretch (Merli et al., 2014; Gottardi et al., 2015). Boreholes and laboratory tests were also part of the large database collected within such comprehensive investigation programme.

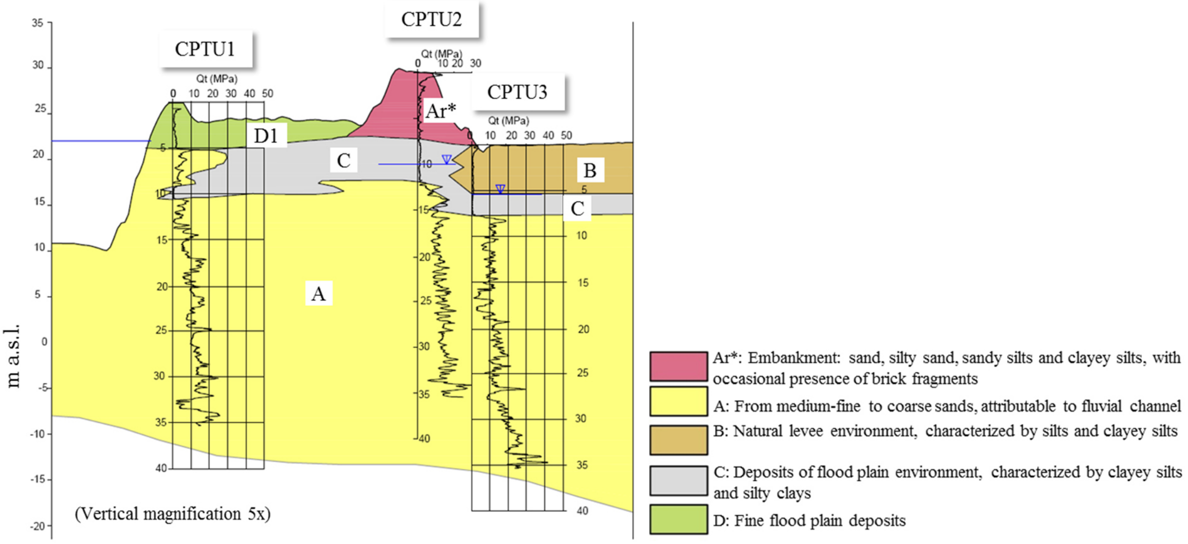

Figure 4. Stratigraphic cross-section in the Province of Reggio Emilia, with location of CPTU tests.

Figure 4 shows the embankment cross section with the location of CPTU tests. A detailed stratigraphic profile has been derived using the classification framework proposed by Robertson (2009), aimed at identifying the *in situ* Soil Behaviour Type (SBT). As an example, results from the application of the method to data from CPTU3 are shown in Figure 5 together with the corrected cone resistance q_t and pore water pressure u profiles. The following well-defined stratigraphic units have been identified using the SBT approach:

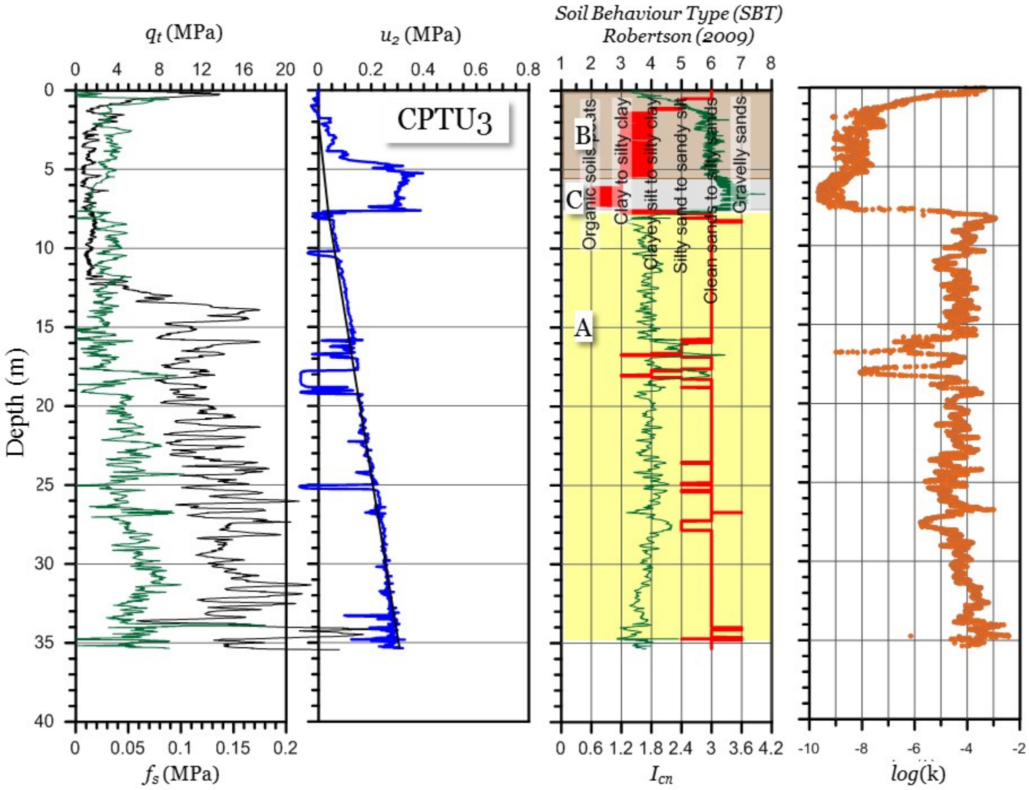

Figure 5. CPTU3 log profiles, classification results and profile of the computed coefficient of permeability in terms of *log*(k).

- Unit Ar, which forms the major embankment and is made up of soils extracted from nearby borrow pits, consisting of an alternation of sands, silty sands, sandy silts and clayey silts (SBT zones 3, 4 and 5);
- Unit D, fine flood plain deposits, consisting of an alternation of clayey silts to sandy silts;
- Unit C, predominantly clays and silty clays (SBT zone 3), with occasional presence of peat and organic soils (SBT zone 2);
- Unit B, alternation of silts and clayey silts (SBT zones 3 and 4);
- Unit A, predominantly sands and silty sands (SBT zone 6).

As a result, the analysis of CPTU measurements provides evidence of a foundation soil consisting of a clay to clayey silt layer, 7-8 m thick, overlying a sandy unit of about 30 m thick, thus confirming that the stratigraphic arrangement is compatible with the typical configuration required for the initiation of backward erosion piping.

In this study, relevant soil parameters have been estimated using some well-known CPTU-based correlations. In particular, soil permeability profiles have been derived using the relationship proposed by Robertson (2010):

$$\begin{aligned} 1.0 < I_c < 3.27 \quad & k = 10^{(0.952-3.04 I_c)} \quad (m/s) \\ 3.27 < I_c < 4.0 \quad & k = 10^{(-4.52-1.37 I_c)} \quad (m/s) \end{aligned} \tag{1}$$

in which I_c is the Soil Behaviour Type index (Robertson, 2009). The hydraulic conductivity (in terms of *log*k) profile deduced from CPTU3 is also plotted in Figure 5. As can be observed, *k* of the aquifer (unit A) is in order of magnitude of $10^{-5} \div 10^{-4}$ m/s.

2.2 The numerical model

The numerical simulation of the groundwater flow leading to the reactivation of a sand boil along the selected cross section has been carried out using the finite element code PLAXIS 3D.

The cross-section geometry has been established using data from topographic surveys, whereas the proposed stratigraphic arrangement relies on the CPTU-based classification results and soil unit identification commented above. As evident from Figure 4, it has been assumed that the sandy unit (referred to as Unit A) extends up to the left boundary of the model, hence such highly permeable layer is present beneath the river bed. Figure 6 shows the finite element mesh eventually adopted, composed 62938 tetrahedral 10-noded elements.

It is worth observing that, in this preliminary attempt to model the reactivation of a sand boil, a vertical cylindrical region (named pipe, hereafter) has been created in the downstream impermeable layer, in correspondence to the real location of the sand boil, being the idea to simulate a “hole type” exit configuration. Furthermore, a semi-spherical region at the base of the cylinder has been considered, aimed at facilitating the flow and make the calculated pressure in the aquifer more realistic. Further field investigations would be required in order to confirm the correctness and effectiveness of such preliminary geometric assumption.

An elastic-perfectly plastic constitutive formulation, based on the Mohr-Coulomb failure criterion, has been adopted for the different soil units, using the available CPTU data for calibration of the soil shear strength.

To model the groundwater flow, an uncoupled analysis has been performed. The initial steady-state condition for the groundwater flow analysis has been generated by considering the average river level over the days preceding the November 2014 high-water event in combination with piezometer readings collected previously (Severi and Biavati, 2013), providing information about water table levels in the land side. Then, the period from 05/11/2014 to 25/11/2014 (Figure 7) has been selected for the transient groundwater flow analysis.

Particular attention has been paid to boundary conditions, and different approaches have been taken into account and compared in some preliminary analyses. The permeable aquifer, overlain by impermeable top layers, results in a semi-confined aquifer with a long leakage length of approximately 1400 m (see also

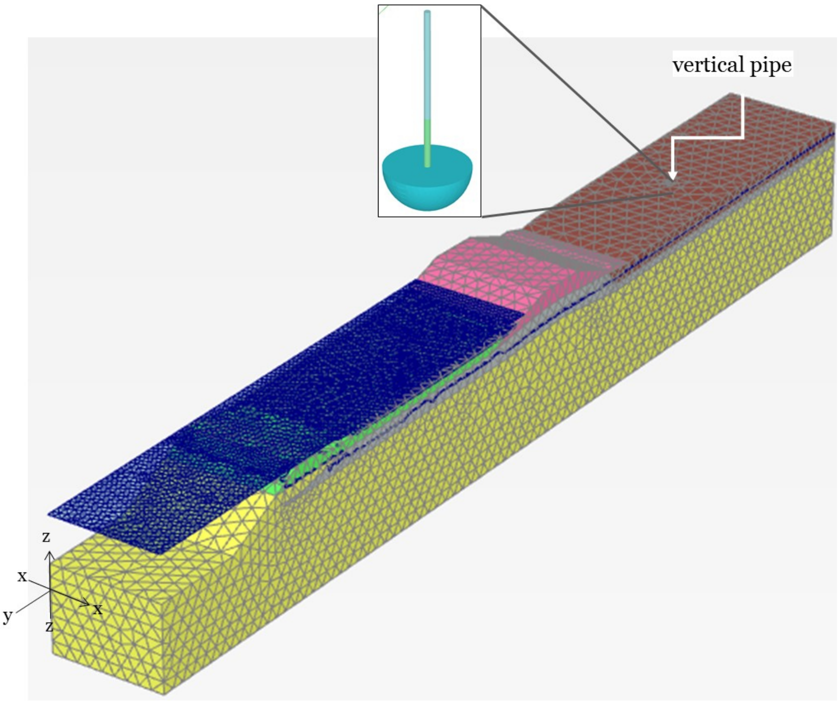

Figure 6. Discretized model of the river embankment, with indication of the soil layering and detail of the vertical pipe.

Bezuijen, 2017) with pressure fluctuations that are still noticeable at a considerable distance from the embankment and the river. The modelling of such a long part of the aquifer using a 3D approach would result in an extremely time consuming analysis. However, assuming a constant piezometric head at the right-hand side of the model (at y_{max}) or a no flow boundary condition will underestimate or overestimate the piezometric head at the vertical pipe respectively. The plot reported in Figure 7 shows the hydraulic boundary conditions (BC) eventually assumed in the numerical model. While the river level fluctuations, as monitored during the whole period of high-water event, has been directly assigned along the riverside model boundary, hydraulic boundary conditions at the right-hand side of the model, referred to the aquifer piezometric level (y_{max}), have been derived from parallel 2D numerical analyses, performed by considering a model long enough to result in a constant hydraulic head with time at the landward side.

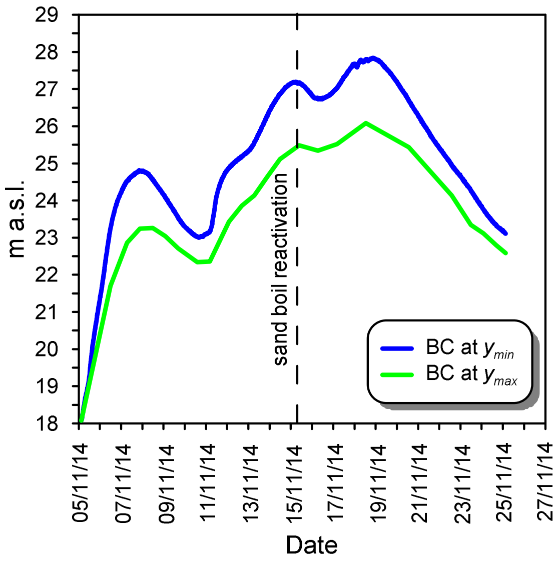

Figure 7. Hydraulic loads evolution within the period of simulation.

The model has been calibrated based upon the USACE (1956) criteria, by which it is accepted that sand boils might occur at an upward gradient through the top stratum of 0.5. Furthermore, sand boils will be observed when the flow velocity in the vertical pipe exceeds the falling velocity of the grains in the sand-water mixture (van Beek, 2015), obtained herein by the application of the Richardson and Zaki (1954) semi-empirical equation:

$$v_z \geq w_t(1-c)^n \tag{2}$$

in which c is the volumetric concentration, n is an empirical determined exponent dependent on the particle Reynolds number, ranging approximately between 4.65 and 2.4, and w_t is the settling velocity for small spherical particles according to Stokes law:

$$w_t = \frac{\rho_s - \rho_w}{1800\eta} d^2 \tag{3}$$

where ρ_s is the density of the single grain, ρ_w is the water density, η kinematic viscosity of the water and d is the grain diameter. Then, assuming for this case of study a uniform initial concentration of 0.55 (or 0.45 of porosity), n equal to 4, ρ_s equal to 2.65 g/cm^3, $\eta = 1.33 \cdot 10^{-5}$ g·s/cm^2 (T = 10º C) and, according to some available grain size distribution curves, $d = d_{50} = 0.22$ mm, it turns out that $v_z \geq 1.4$ mm/s. Although parameters assumed are based on the known range of possible real values, predictive accuracy should be improved with further calibrations such as particle size distribution of sediments within the vertical pipe or discontinuity.

From the above-mentioned, and in the absence of any further information, the model has been calibrated to match $i \geq 0.5$ e $v_z \geq 1.4$ mm/s. Sensitivity analyses have shown that the parameters which have a major influence on the results are the coefficient of permeability of the aquifer and of the vertical pipe, the diameter of the pipe, the presence of a high permeability region at the interface between the pipe and the aquifer and the model width.

At this preliminary stage of development, two aspects of the model have been calibrated: the hydraulic conductivity of the vertical pipe as well as its diameter. On the other hand, the permeability of the aquifer has been determined using Eq. (1), the diameter of the semi-spherical region at the pipe base has been set to 4 m and the width of the model used is equal to 40 m.

Figure 8 shows the results of the model calculations, in terms of average vertical gradient along the pipe ($\Delta h/L_{pipe}$) and average vertical flow velocity (v_z, in mm/s) at the time the sand boil reactivated, for pipe permeability (k_{pipe}) varying linearly with the permeability of the aquifer. The permeability of the semi-

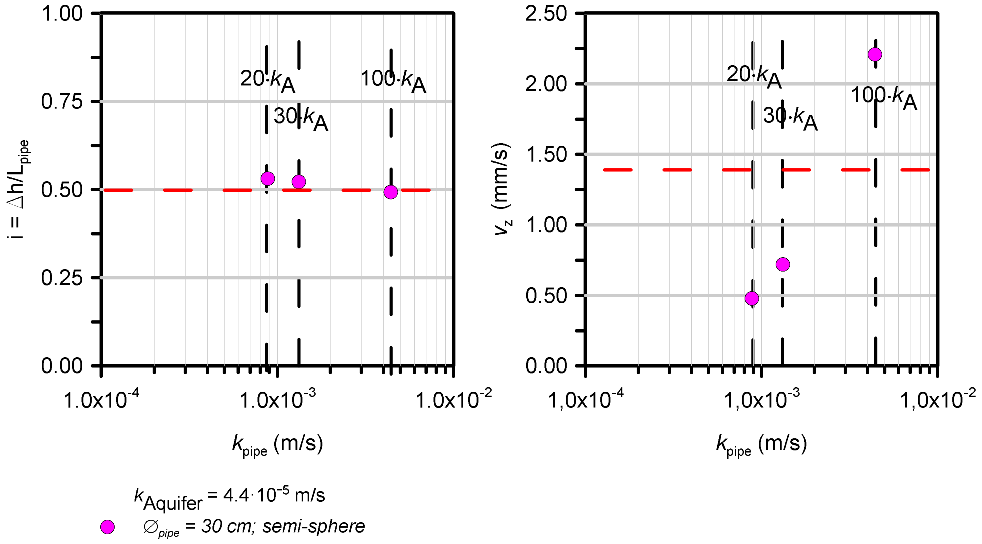

Figure 8. Predicted average vertical gradient along the pipe and average vertical flow velocity.

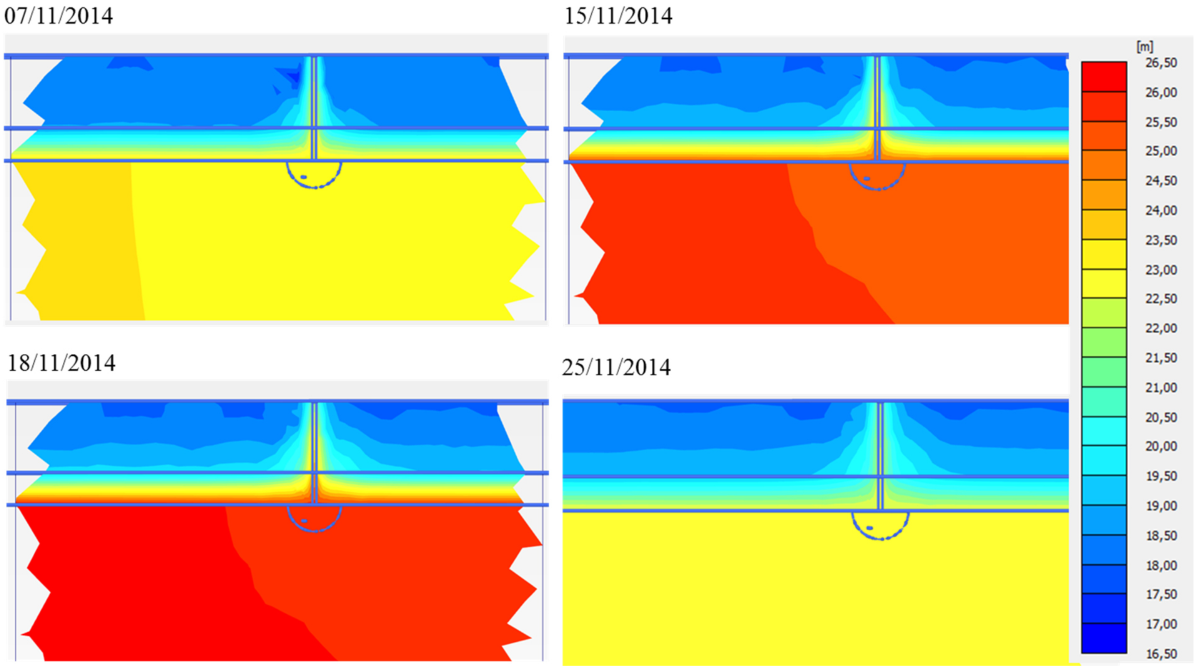
07/11/2014
15/11/2014
18/11/2014
25/11/2014

Figure 9. Countour plots of groundwater head in the y-z plane at different stages of the simulation.

spherical cluster was set equal to k_{pipe}. As can be clearly observed, the gradient decreases and velocity increases when k_{pipe} is increased, being v_z much more sensitive. Final calibrated parameters are Ø 30 cm (for the pipe) and $k_{pipe} = 100 \cdot k_{aquifer} = 4.4 \cdot 10^{-3}$ m/s. It is worth remarking that greater diameters of the pipe were found not to fulfil the criteria adopted for the sand boil reactivation, also taking into account that such values would be rather unrealistic. Further observations and detailed investigations, not currently available, would certainly help in confirming the reliability of the outcomes from calibration analyses.

Figure 9 shows the contour plots of groundwater head, in the y-z plane passing through the pipe, computed with PLAXIS 3D at three different stages. Finally, the calibrated model has been verified for the November 2016 high-water event, in which the sand boil did not reactivate. Indeed, both hydraulic gradient and vertical flow velocity at the peak flow were significantly smaller than those obtained for the 2014 event.

3 CONCLUSIONS

This paper has proposed a numerical study aimed at providing a better insight into the groundwater conditions leading to the reactivation of sand boils at the toe of river embankments. The analysis has been carried out with reference to a specific segment of the Po river embankments, located in the province of Reggio Emilia (Northern Italy), which has experienced recurrent piping phenomena over the last two decades, the latest having occurred during the 2014 major high-water event.

According to the available in-situ testing data, the resulting stratigraphic arrangement of the foundation subsoil has turned out to be fully consistent with soil layering configurations typically affected by backward erosion piping. The geotechnical parameters of the different soil units, including permeability, have been carefully determined from piezocone tests, although a certain spatial variability and thus heterogeneity are very likely to affect the whole river embankment system and could be taken into account in a more advanced interpretation model.

In order to simulate properly the reactivation of a sand boil, the presence of a pre-existing outflow exit has been included in the discretized FE model as a vertical pipe. Its dimension, as well as its hydraulic conductivity, have been determined by back-analysis, taking into account some well-recognized criteria found in the literature (e.g. USACE) for sand boil reactivation.

The preliminary sensitivity analyses have allowed identifying the parameters having a major influence on the model performance. In particular, the crucial role played by both the diameter and the coefficient of permeability of the vertical pipe suggests the need for further investigations and more detailed information on the geometry and the granular soil characteristics of such volume.

On the other hand, the proposed numerical model seems to simulate properly the response of the embankment, as observed in the last high-water events. Indeed, the numerical results, while confirming the occurrence of a sand boil after the 2014 event, have correctly shown that the river water level evolution monitored in November 2016 would not lead to a sand boil reactivation.

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