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Numerical Prediction of the Drying-Wetting Process in a River Levee and Floodplain

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Abstract – One third of the economic losses due to natural disasters in the last century has been caused by floods. Today the flood hazard is increasing due to more frequent extreme hydrological events, caused by climate change, and to the land use change and urbanization, that reduce the water storage capacity of the subsoil and the floodplain areas. An appropriate planning of river levees and floodplains is required to protect inhabited areas and infrastructures. At the same time, an efficient management, assisted by effective monitoring and prediction tools, ensures the performance of the defence systems. In this context, a land reprofiling was designed for river Secchia in Northern Italy, to widen the natural floodplain. In the paper the response of the new system to flood events is assessed by finite element analyses able to describe the soil-water-atmosphere interaction. The reliability of the numerical prediction relies on a proper description of both the hydraulic behaviour of the unsaturated soil, i.e. the water retention curve and the permeability function, and the external load history, established from the hydraulic and atmospheric boundary conditions. Indirect methods for the estimation of the Soil Water Retention Curve may involve significant limits if not combined with a laboratory information on the soil nature and state. Moreover, the numerical results show that the drying-wetting process is highly dependent on the initial saturation conditions of the subsoil, thus making it essential to simulate a sufficiently long load history.

***Keywords*:** Flood Defence Systems, Unsaturated Soil, Soil-Water Retention Curve, Environmental Loads, Code_Bright

1. Introduction

Recent databases show that the economic losses due to natural disasters have increased in the last century and that around a third of them has been caused by floods. At the same time the death tolls, relative to population, have decreased thanks to better planning and preventive measures [1]. In the changing climate age, the consequences of the progressively warming atmosphere are an accelerating water cycle and more intense and frequent extreme hydrological events. Moreover, non-climatic factors, especially related to the change in the land use, compound the flood hazard by reducing the water storage capacity of the subsoil and the floodplain areas [2,3]. In the face of the awareness that the growing flood hazard should not be overlooked, appropriate planning and management of river flood defence systems are required, where floodplains and levees contribute to the safety of inhabited areas and infrastructures [4]. The widening of floodplains is one of the measures that, among other ecological and naturalistic benefits, reduce the flood risk [5].

In this context, the reprofiling of a defence system was designed for river Secchia in Northern Italy, consisting in displacing the old levee with a new one located at a larger distance from the river. The response of the new system to external loads can be assessed by numerical methods able to describe the complex soil-water-atmosphere interaction, provided that the soil hydraulic behaviour in unsaturated conditions and the environmental and hydraulic load history are accurately modelled. In fact the behaviour of soils in unsaturated zones, being the result of coupled thermo-hydro-mechanical processes in a three-phase porous medium, requires a suitable modelling based on the ground-atmosphere interaction mechanisms and on continuity equations, that can be more easily approached by numerical methods rather than analytical solutions [6].

In the following, the case study and the soil properties are described, with an emphasis on the characterization of the soil water retention curve and the permeability function. Then the drying-wetting process in the levee and the floodplain, induced by rainfalls and flood events, is discussed on the basis of finite element analyses that take into account the history of the water level variations and of the interaction with the atmospheric conditions. The results allow to get insights in the sensitivity of the analysis on the input parameters, especially the soil hydraulic properties and the initial saturation conditions of the levee and the floodplain, the latter influenced by the environmental load history that predates the flood event.

2. Case Study
2.1. History of the Site
The river Secchia is one of the main right tributaries of river Po, in Northern Italy, and is characterized by low water in summer and floods in spring and autumn, like many rivers from the Apennines. In 2014, a breach in the right levee in suburban Modena city caused the release of about 36×10^6 m^3 of water on a plain area of 52 km^2, with a peak flow discharge of about 434 m^3/s [7].

Among the safety and restoration actions undertaken after the event, a reprofiling of the water defence system was designed upstream to Ponte Alto and the city, covering about 1 km of the river (Fig. 1). The works consisted in the complete removal of the old levee and the construction of a new earthen embankment at a larger distance from the river, to widen the natural floodplain (Fig. 2). The new embankment has a height of 4.5 m and a length at the base of 24.5 m, while the new floodplain has an average horizontal extension of about 30 m and an elevation of 36.5 m a.s.l. [8]. The riverbed has an elevation of 28.5 m a.s.l.

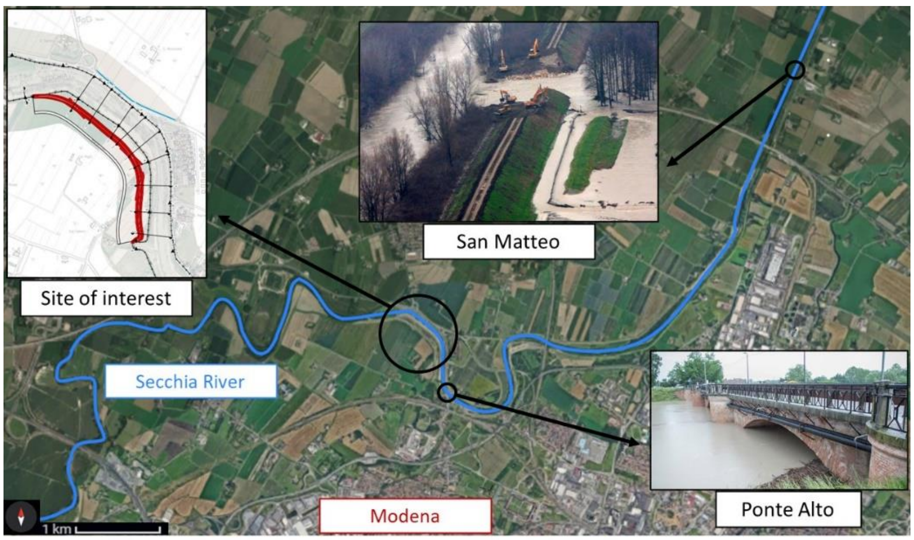

Fig. 1: Secchia river north to Modena city: locations of the breach failure in S. Matteo (2014) and of the site of the reprofiling intervention (2018) upstream to Ponte Alto [courtesy of Civil Protection Department, Italy].

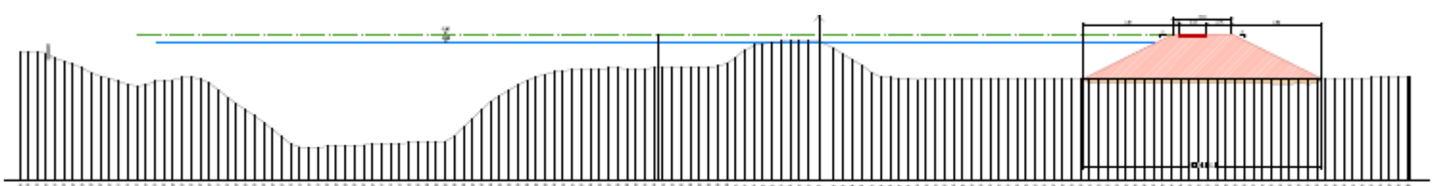

Fig. 2: Representative section showing the Secchia riverbed on the left, the old levee later removed in the centre, and the new earth embankment on the right (units m), after [8].

2.2. Material Properties
The basic geotechnical properties of the considered soil, such as particle-size distribution, Atterberg limits and compaction characteristics (i.e. dry unit weight and void ratio), were assessed in laboratory on disturbed samples from the old levee. The results were compared with the design properties of the soil constituting the new levee to verify whether the collected material could be considered representative of the behaviour of the newly built water defence structure. Having %Cl=21, %Si=50 and %Sa=29, the material can be classified as sandy silt with clay; the Atterberg limits are w_L=28.3% and

w_P=19.8%, resulting in I_P=8.5%. The values of optimum water content w_{opt}=16% and standard maximum dry unit weight γ_d=17.5kN/m^3 have been determined from standard Proctor compaction curve; the void ratio is $e = 0.52$.

The hydraulic response of unsaturated soils subjected to environmental loads is linked to their water retention and hydraulic conductivity properties. In order to model the physical processes related to the unsaturated soils behaviour, the the definition of the soil-water retention curve (SWRC) and of the hydraulic conductivity (*k*) function is required. The direct direct estimation of these parameters is often costly and time consuming and, sometimes, unfeasible. Therefore, they are here here estimated through indirect methods which, by means of appropriate pedotransfer functions or physical-statistical models, allow for their assessment starting from routinely geotechnical characteristics that can be measured in an easier and faster way. For the sake of brevity, the formulation of the different literature models is not reported here [6].

From the geotechnical properties above reported, nine different water retention curves and hydraulic conductivity functions were estimated for the considered soil. Figure 3 shows the predictions obtained from the different indirect methods (grey lines), where Ψ is the suction, S_e is the effective degree of saturation and k_r is the relative permeability.

The range of variability of the predicted curves is quite broad and it is not possible to identify methods more reliable than others, unless additional information is available, such as on site monitoring data that could solve the uncertainties by back-analysis procedures. In default of these, the predictive capability of the different indirect methods cannot be established a priori. Therefore, for the practical purpose, to overcome the problem of the reliability of the single indirect method, a range of variation of the water retention curve and of the hydraulic conductivity function has been defined [9]. The upper (red) and lower (blue) bounds, represented in Figure 3, have been introduced according to the van Genuchten's SWRC model [10], the same terms have been associated to the hydraulic conductivity functions of soils characterized by the same features.

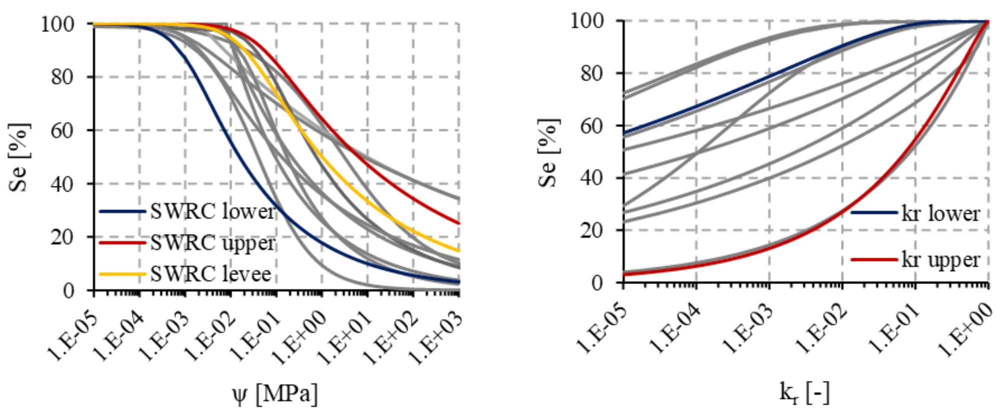

Fig. 3: Ranges of variability of the SWRC and the hydraulic conductivity function for the considered soil from indirect estimation methods, with upper (red lines) and lower (blue lines) bounds.

Considering the large variability of the hydraulic parameters, numerical sensitivity analysis on an ideal model has been performed. The analysis has been conducted on a 1D soil column (20m x 5m), by means of the finite element code Code_Bright [11], that allows to perform hydro-thermo-mechanical analyses in three-phases porous media. Boundary conditions have been set to simulate the complex soil-atmosphere interactions: time dependent evaporation, rainfall, radiation and heat exchanges on the upper boundary, while the other boundaries are considered perfectly impervious and adiabatic. Ideal uniform initial conditions in terms of saturation and temperature have been set over the entire domain. A five-month period, namely July-November 2019, was simulated; the details related to the numerical model are reported in Section 3. The results show a high sensitivity of the response of the soil to the constitutive parameters: the SWRC governs the depth and the velocity of the saturation front propagation, while the k function, defining the amount of the hydraulic soil-atmosphere exchanges, governs the mean value of the degree of saturation.

Therefore, in the modelling of engineering problems that involve partially saturated soils, it is fundamental to pay attention to the definition of the SWRC and of the hydraulic conductivity function by considering an additional information from laboratory tests or on-site investigations. The shape of the SWRC is influenced by the soil structure [12]; therefore, combining the results from indirect methods with the information on the nature and state of the soil, a curve describing the average expected behaviour has been defined, represented with yellow line in Figure 3.

These findings, together with empirical considerations, have been applied to the analysis of the case study (Section 3), where particular attention has been paid to all the elements that govern the thermo-hydraulic problem and contribute to set the condition of partial saturation typical of earth embankments, such as: soil-atmosphere interaction phenomena, the hydraulic loads due to exceptional flood events and the ground conditions prior to the event of interest. The hydrometric and atmospheric data were collected from the databases of the Environmental Protection Regional Agency (ARPA Emilia Romagna).

2.3. Hydraulic and Environmental Load Conditions

The river water level data are registered in Ponte Alto station, located downstream with respect to the site of interest. These hydrometric data were collected from January to December 2019 and, in order to recognize the extreme events, they were compared with the hydrometric threshold values for the flood hazard established by ARPA Emilia Romagna, namely the thresholds 1, 2 and 3 for respectively ordinary, moderate and high hazard conditions.

The water level history simulated in the analyses is represented in Figure 4 and compared with the simplified contour of the case study. It can be observed that the water level remains overall constant over the year at the elevation of about 29 m a.s.l.; this condition persists until extreme flood events (i.e. May and November 2019) drastically modify the hydrograph causing, in most cases, the exceeding of the water level thresholds.

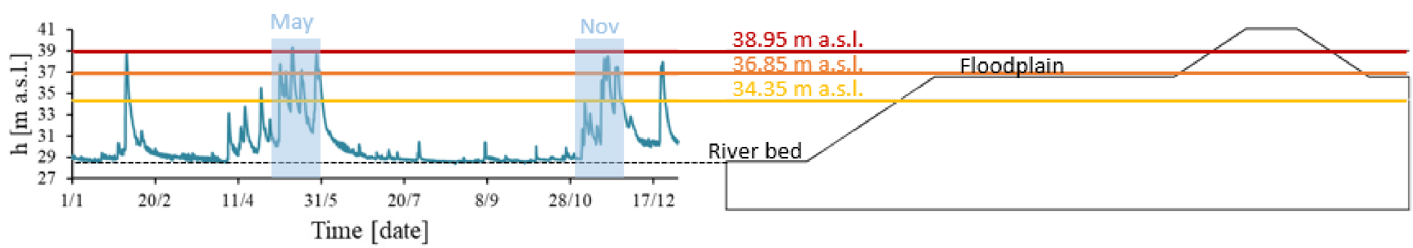

Fig. 4: River Secchia water levels in 2019 simulated in the analyses and schematization of the geometry of the case study (the horizontal scale is not respected). The hydrometric thresholds 1, 2 and 3 are represented respectively in yellow, orange and red.

The data related to environmental load conditions, such as rainfall, temperature, relative humidity, wind velocity and radiation, have been collected from January to December 2019, at different stations located close to the site of interest. The environmental load histories simulated in the analyses are represented in Figure 5, from the registered daily average values.

3. Numerical Analysis and Results

3.1. Numerical Model and Simulated Scenarios

As stated above, the proper simulation of the hydraulic response of the water defence system to flood events requires to model the unsaturated soil behaviour and the soil-atmosphere interaction. The finite element code Code_Bright was used to this purpose [11], limiting the analysis to the hydro-thermal coupling.

The schematic geometry shown in Figure 4 was considered, with the material properties and the external load conditions introduced in Sections 2.2 and 2.3. In the perspective of hydro-thermal analyses, soil thermal properties were also introduced based on literature data: a solid grain specific heat equal to 840 J/(kg·K) and a thermal conductivity dependent on the saturation degree in the range 0.5-1.7 W/(m·K), associated with dry-saturated conditions. The isotropic saturated hydraulic conductivity was set equal to 10^{-7} m/s.

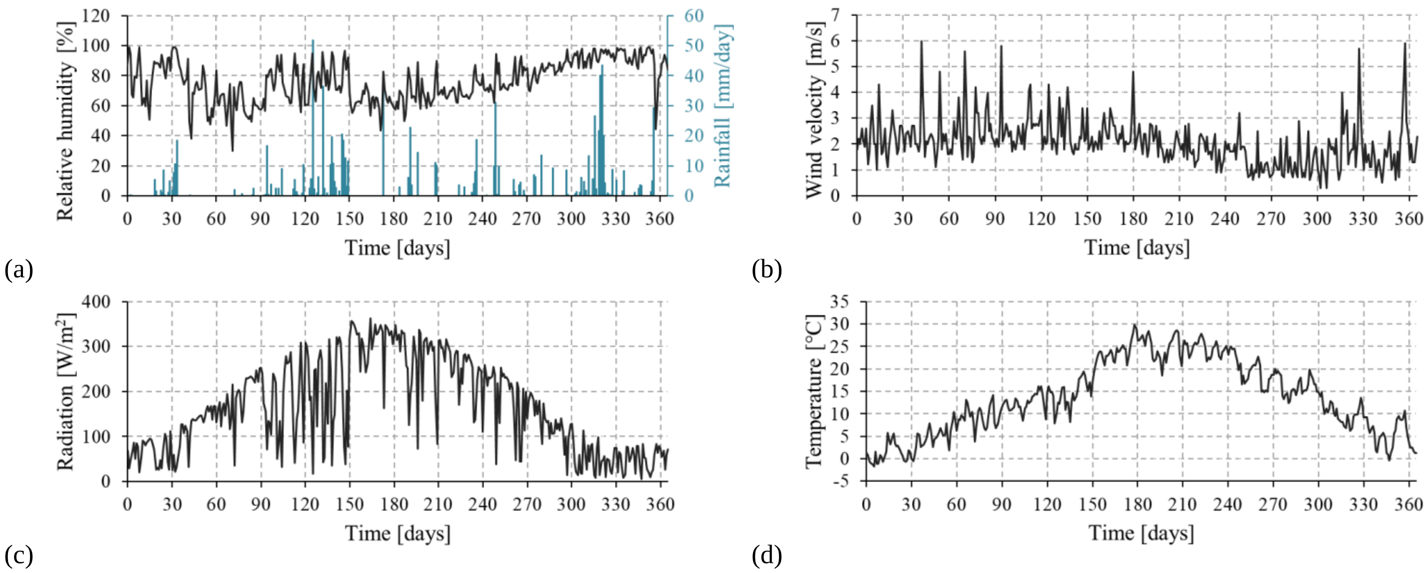

Fig. 5: Environmental load history over the year 2019 used in the numerical analyses: (a) air relative humidity and rainfalls, (b) wind velocity, (c) radiation and (d) air temperature (daily average values).

For the given geometric contour, it is expected that the drying-wetting process in the new levee is mostly affected by air conditions and rainfall events, while the process in the floodplain is affected also by the water levels of the river. Two different scenarios were analysed, to investigate the effects of flood events of similar intensity on a subsoil at the different initial conditions that result from different hydro-meteorologic histories before the event (Figs. 4 and 5). With the scenarios A and B, two flood events are investigated, respectively occurring in November at the end of a 7-months period (A: 1.6.2019-31.12.2019) and in May at the end of a 5-months period (B: 1.1.2019-31.5.2019). The time scale has been discretized with 1-day intervals. Further details on the time discretization and on the assumed initial conditions of temperature and saturation are provided in reference [13].

3.2. Results and Discussion

For the sake of brevity, in the following only the results obtained with the assumptions of the so labelled “SWRC-levee” curve and “kr-upper” permeability function are discussed (Fig. 3). In fact, the influence of the SWRC is shown only in Figure 6, with reference to the drying-wetting process at the toe of the new levee. As expected, the SWRC-upper curve is always associated with higher saturation conditions, as far as the rainfall events play the major role, but the discrepancy tends to vanish when the flood events gain relevance in the saturation process (November in scenario A and May in scenario B).

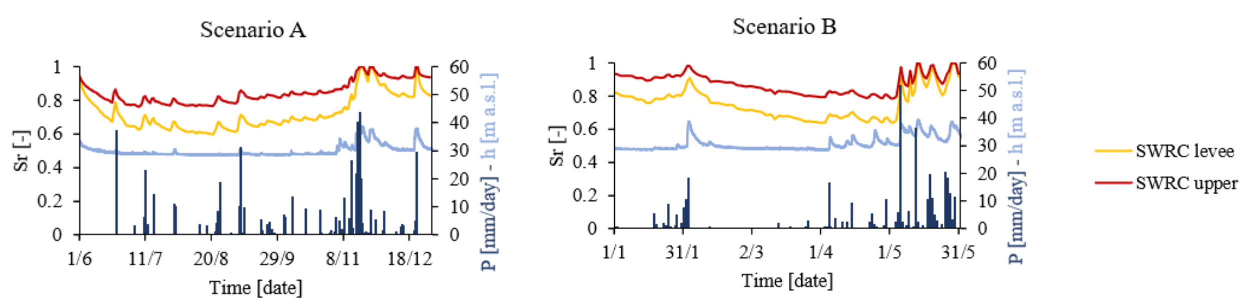

Fig. 6: Variation of the saturation degree with time at the toe of the new levee, with different SWRC and in A and B scenarios. The graphs also report the rainfalls P [mm/day] and the river water level history h [m a.s.l.].

Figure 7 shows the drying-wetting process for the two scenarios and for two significant positions, i.e. the symmetry axis of the new levee and the central axis of the floodplain, at three different depths, up to 2 m from the ground surface. It is worth commenting that the sharp variations in the saturation degree occurring at the ground surface (red curves) smoothen rapidly at relatively shallow depths.

The comparison between the saturation degrees at the deepest positions from the two scenarios (15 m for the levee, 10.5 m for the floodplain – yellow lines) points out the influence of the initial conditions in the drying-wetting process. In fact, the process of wetting at depth is faster for the scenario A than for B, since for A the initial degree of saturation is higher as the result of previous rainfalls in the months preceding November, and therefore the soil hydraulic conductivity is also higher. On the contrary, for the scenario B the drier initial condition, resulting from scarcity of rainfalls in the months preceding May, induces a lower hydraulic conductivity and consequently a slower process of wetting.

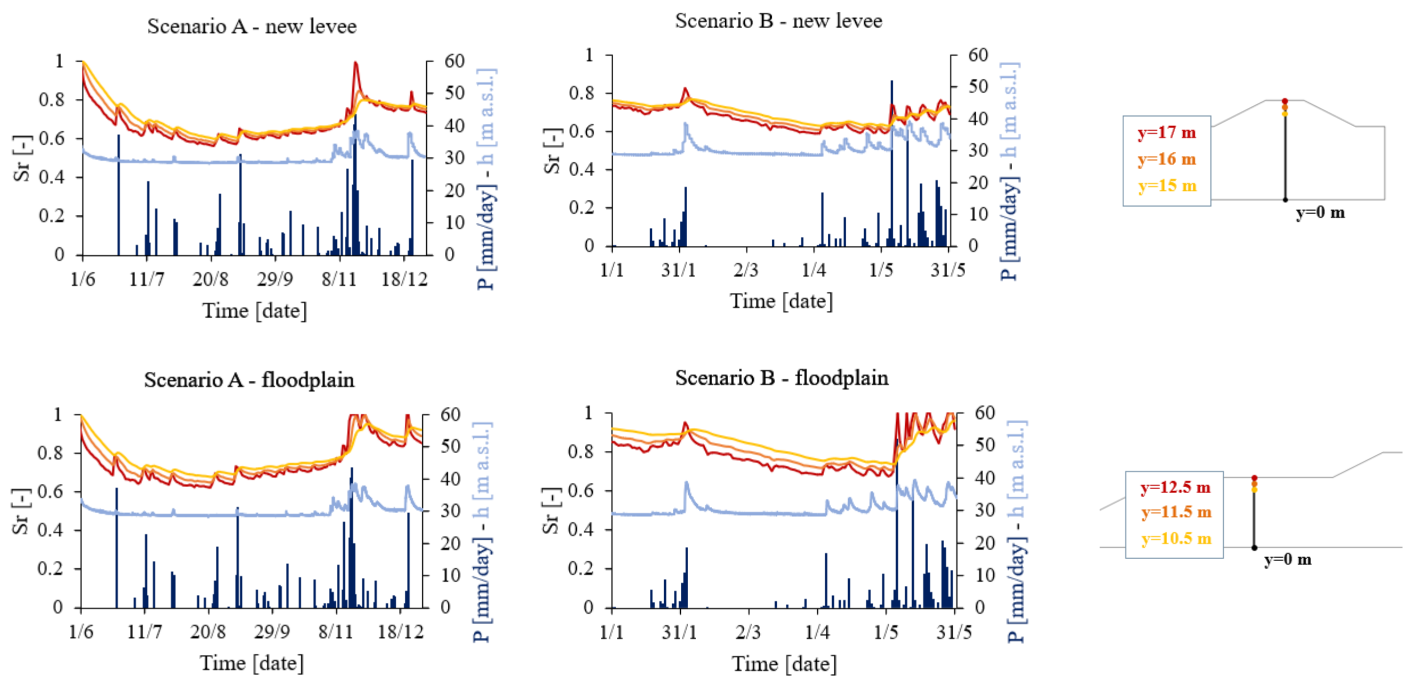

Fig. 7: Variation of the saturation degree with time and with depth, at the centre of the new levee and of the floodplain, for the scenarios A and B. The graphs also report the rainfalls P [mm/day] and the river water level history h [m a.s.l.].

The wetting process can be examined also in Figure 8, showing the profiles of the saturation degree along the same vertical axes and their evolution with time. According to the characteristics of the water defence system, intense or prolonged rainfall events are considered as significant for the position on the new levee (Fig. 8.a), while the exceptional peaks in the river water level are considered for the position in the floodplain (Fig. 8.b). The red solid and dashed lines represent the saturation degree profile respectively before and after the sequence of investigated events and show that the initial average saturation degree of the soil is higher in November (scenario A) than in May (scenario B). This different initial condition, at both (a) and (b) positions, explains the faster wetting process of scenario A vs. B (blue vs. green curves).

Moreover, the complex mechanism of water migration in the unsaturated soil is highlighted by the movement of the water table at depth. In the floodplain position (b), there is a negligible movement of the water table, due to the proximity to the river, while in the levee position (a) the water content balance leads to a partial drying effect at depth and a water table lowering.

As a conclusion, looking at the rainfalls on the levee and at the floods on the floodplain, the environmental and hydraulic loads occurring in November period, regardless their intensity and duration, may be in general more dangerous than those of May period, because they reach a soil characterized by higher degree of saturation and therefore more permeable.

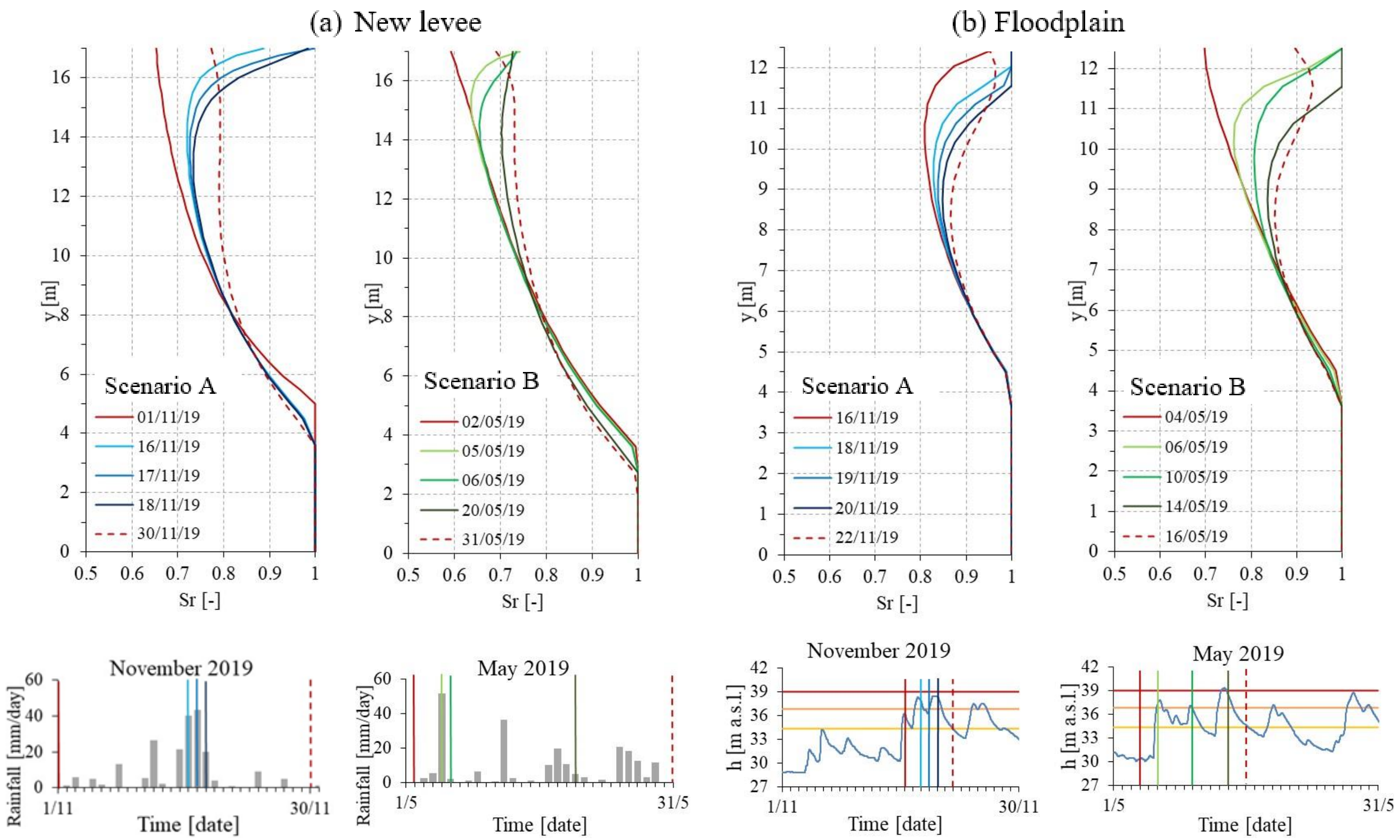

Fig. 8: Evolution of the saturation profiles: (a) at the centre axis of the levee at significant rainfall events, (b) at the centre of the floodplain at exceptional flood events.

4. Conclusions

To increase the safety of inhabited areas and infrastructures, the reprofiling of a water defence system was planned for river Secchia in Northern Italy and the old levee was displaced with a further one to widen the natural floodplain.

The response of the new system to hydraulic and environmental loads was assessed by hydro-thermal numerical analyses performed with Code_Bright code, to describe the complex soil-water-atmosphere interaction. Such an accurate tool has reliable predictive capabilities provided that the required input parameters are correctly estimated, such as the soil hydraulic behaviour in unsaturated conditions and the environmental load history. The study here presented is a preliminary investigation and in order to adopt this kind of approach for a reliable prediction it is recommended to compare the numerical results with on site observations of the variables of interest and quantify, in such a way, the accuracy of the model's predictions. Particularly, the validation of the numerical model could be conducted using the information provided by ERT (Electrical Resistivity Tomography) technique which is useful for monitoring the evolution in time of the hydrological variables in the soil, at different depths [14]; this non invasive on-site technique is economic and less time consuming with respect to other geotechnical surveying methods.

The indirect methods for the assessment of the SWRC and the permeability function leave unresolved an uncertainty issue and should be integrated with additional investigations on the nature and state of the soil. When dealing with such uncertainty, it is highly recommended to perform a sensitivity analysis in order to evaluate the influence of the parameters on the numerical results; particular attention should be paid to the SWRC whose definition plays a major the description of the behaviour of unsaturated soils subjected to either rainfalls or flood events.

The numerical results on the drying-wetting process in the levee and the floodplain show that the evolutive process is influenced not only by the intensity and duration of the external cause (mainly rainfalls for the defence levee and flood events for the floodplain), but also by the soil initial conditions, due to the dependence of the hydraulic conductivity and retention properties on the degree of saturation. Therefore, the study of the evolution of the environmental loads and of the soil saturation is highly relevant in the context of the verification of water defence systems.

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References

[1] J. Daniell, “Natural disaster since 1900: over 8 million deaths and 7 trillion US Dollars damage,” in *KIT Press Release, Karlsruhe Institute of Technology*, vol. 58, pp. 1-5, 2016.

[2] T. K. Andersen and J. M. Shepherd, “Floods in a changing climate,” *Geography Compass*, vol. 7/2, pp. 95-115, 2013.

[3] Z. W. Kundzewicz, Y. Hirabayashi and S. Kanae, “River floods in the changing climate - Observations and projections,” *Water Resour. Manage.*, vol. 24, pp. 2633-2646, 2010.

[4] F. Buijs, J. Simm, M. Wallis and P. Sayers, “Performance and reliability of flood and coastal defences,” *R&D Technical Report FD2318/TR1, Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme*. UK Department for Environment Food & Rural Affairs, 2007.

[5] European Environment Agency, “Flood risks and environmental vulnerability – Exploring the synergies between floodplain restoration, water policies and thematic policies,” *EEA Report 1/2016*, 2016.

[6] D. G. Fredlund, H. Rahardjo and M. D. Fredlund, *Unsaturated soil mechanics in engineering practice*. Hoboken, New Jersey: John Wiley and Sons, 2012.

[7] S. Orlandini, G. Moretti and J. D. Albertson, “Evidence of an emerging levee failure mechanism causing disastrous floods in Italy,” *Water Resour. Res.*, vol. 51, pp. 7995-8011, 2015.

[8] Agenzia Interregionale per il fiume Po, “MO-E-1323 – Stralcio B.1.8. Intervento di riprofilatura e realizzazione nuovo argine in DX a monte di Ponte Alto,” *AIPo Internal Report*, 2016.

[9] M. Caruso and C. Jommi, “An evaluation of indirect methods for estimation of hydraulic properties of unsaturated soils,” in *Proceedings of International Conference on Problematic Soils* 1, pp. 183-191, 2005.

[10] R. van Genuchten, “A closed-form equation for predicting the hydraulic conductivity of unsaturated soils,” *Soil Sci. Soc. Am. J.*, vol. 44, pp. 892-898, 1980.

[11] S. Olivella, A. Gens, J. Carrera and E. E. Alonso, “Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media,” *Engineering Computations*, vol. 13, pp. 87-112, 1996.

[12] S. K. Vanapalli, D. G. Fredlund and D. E. Pufahl, “The influence of soil structure and stress history on the soil-water characteristics of a compacted till,” *Géotechnique*, vol. 49, pp. 143-159, 1999.

[13] C. Rossignoli, “Analisi della risposta di argini fluviali alle sollecitazioni ambientali,” (in italian) M.Sc. dissertation, Politecnico di Milano, Italy, 2020.

[14] M. Chrétien, J. F. Lataste, R. Fabre and A. Denis, “Electrical resistivity tomography to understand clay behavior during seasonal water content variations,” *Engineering Geology*, vol. 169, pp. 112-123, 2014.