Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

On the effect of intrinsic soil variability on the stability assessment of river embankments in partially saturated conditions

Effet de la variabilité intrinsèque du sol sur l'évaluation de la stabilité des berges des rivières en condition de saturation partielle

Guido Gottardi, Carmine G. Gragnano, Marco Ranalli & Laura Tonni
Department of Civil, Chemical, Environmental and Materials Engineering, DICAM, Alma Mater Studiorum – Università di Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

ABSTRACT: The unavoidable uncertainty in the limit state analysis of geotechnical systems is typically taken into account by current international standards via a semi-probabilistic approach with the introduction of suitably defined partial safety factors. However, these assumptions are not always applicable consistently; with the aim of carrying out a more realistic stability assessment of river embankments under transient seepage, for instance, the hydraulic parameters defining the evolving partially saturated soil state should be included in the analyses of the actual probability of failure, Pf. At the same time, such more advanced analyses should not use deterministic values of relevant parameters, as their intrinsic variability may strongly affect the resulting Pf. In this case, a fully probabilistic analysis should be introduced instead, as with the Monte Carlo method, which can turn out to be very demanding computationally. With a less rigorous formulation, other probabilistic approaches, like the well-established Point Estimate Method (PEM), enable to detect efficiently the effect of parameters variability on the final outcome and are still sufficiently reliable and relatively easy-to-use, being already implemented in various commercial numerical codes. In such context, the paper aims at carrying out a critical appraisal of the outcome of a detailed study on a specific river embankment in Northern Italy, which experienced a catastrophic sudden collapse in 2014. The results obtained with PEM allow to identify the crucial role of suction distribution and clearly show that the Pf of the riverbank slopes can be significantly underestimated when the variability of hydraulic parameters is neglected.

RÉSUMÉ : Les plusieurs sources d'incertitude dans l'analyse à l'état limite des systèmes géotechniques sont généralement prises en compte par les différentes normes internationales à travers une approche semi-probabiliste basée sur l'introduction de facteurs de sécurité partiels. Néanmoins, les hypothèses à la base de ce type d'analyse ne sont pas toujours applicables de manière cohérente. Par exemple, afin d'évaluer d'une manière plus fiable la stabilité des berges de rivières soumises à filtration en régime transitoire, le calcul de la probabilité de rupture (Pf) devrait prendre en compte les paramètres hydrauliques qui décrivent l'état du sol partiellement saturé. En même temps, il faudrait considérer la variabilité intrinsèque de ces paramètres, car cela peut affecter considérablement la valeur résultante de Pf. Dans ce cas, une analyse entièrement probabiliste devrait donc être effectuée, à l'aide par exemple de la simulation de Monte Carlo dont le coût calculatoire est toutefois très élevé. D'autres approches de simulation simplifiées, telles que la Méthode d'Estimation Ponctuelle (PEM), permettent d'évaluer d'une manière satisfaisante l'effet de la variabilité des paramètres sur le résultat final et résultent suffisamment fiables et simples à utiliser, étant déjà mis en œuvre dans plusieurs logiciels. Dans ce cadre, l'article présente une évaluation critique des résultats d'une étude concernant la stabilité d'une berge de rivière au nord d'Italie, où une rupture massive de talus en 2014 a produit une brèche. Les résultats obtenus à l'aide de la méthode PEM permettent de reconnaître le rôle clé de la distribution de la succion et montrent que la probabilité de rupture des berges peut être considérablement sous-estimé lorsque la variabilité des paramètres hydrauliques n'est pas prise en compte.

KEYWORDS: probabilistic analysis, Point Estimate Method, embankment stability, unsaturated soil, transient seepage

1 INTRODUCTION.

International standard codes provide for the use of a semi-probabilistic approach in the geotechnical limit state analysis, in order to take into account the presence of uncertainty in actions and resistances. The semi-probabilistic approach considers partial safety factors, specifically defined for the different types of actions and soil resistance parameters. However, this method is not applicable consistently to any geotechnical stability problem. For instance, within the stability assessment of river embankments under transient seepage conditions, the soil resistance is also affected by the hydraulic parameters, which define the evolving partially saturated soil state and should therefore be included in the analysis in order to describe the actual response (Rinaldi et al. 2004; Liang et al. 2015).

Nevertheless, the partial safety factor approach cannot be used for these parameters, since it is not possible to define a priori whether their contribution is favourable or unfavourable towards a specific collapse mechanism. At the same time, a deterministic use of the hydraulic parameters is not advisable, because their intrinsic variability may strongly affect the results (Phoon et al. 2010; Cho 2012).

In such context, a fully probabilistic analysis should be adopted instead of a semi-probabilistic approach, in order to take into account all relevant uncertainty sources and thus obtain the actual margin of safety of the embankment towards stability. In this respect, despite the large number of studies dealing with reliability analysis of slopes, (Santoso et al. 2011; Ranalli et al. 2014; Zhang et al. 2019), few contributions have focused so far on river embankment stability (Amabile et al., 2020; Gottardi et al. 2020).

In order to gain a better insight into such geotechnical issue, the paper discusses results of a probabilistic study which was carried out to specifically investigate the role of the intrinsic variability of unsaturated soil hydraulic properties in reliability analyses of existing river embankments.

The study makes use of a valuable geotechnical dataset, including in situ and laboratory tests, collected in a stretch of the Secchia River after the occurrence of a catastrophic embankment breach in 2014 (Gottardi and Gragnano, 2016). This watercourse is a right tributary of the major River Po, flowing north of the historic town of Modena (Italy) in a densely populated and economically important area.

Two series of probabilistic limit equilibrium analyses, performed under transient flow conditions as induced by fluctuating river levels and rainfall events, are shown and the effect of assuming hydraulic parameters either as deterministic or random variables is examined with respect to the resulting probability of failure of the river embankment.

The well-established Point Estimate Method (PEM) is used as probabilistic tool, since it allows to easily but efficiently incorporate spatial variability of soil properties into reliability analysis, propagating the uncertainty from the geotechnical and hydraulic input parameters to the stability safety factor.

2 CASE STUDY

2.1 *In situ and laboratory geotechnical tests*

The probabilistic study proposed in this paper was carried out with reference to a specific, thoroughly investigated 20 m-long segment of the river Secchia banks, which suddenly collapsed after a period of intense rainfall, in January 2014. Figure 1 shows a layout of the in-situ tests carried out after the collapse in order to obtain information useful to identify the probable mode of failure and used as reference dataset for the analyses contained herein. For each alignment, a borehole (BH) and a seismic piezocone test (SCPTU) were carried out from the crest of the bank and pushed to approximately 30 m in depth; two additional piezocone tests (CPTU) were carried out at the berm and close to the outer slope toe.

The laboratory experimental programme included a significant number of tests for the determination of basic physical properties of soils, Atterberg limits, particle size distribution, in conjunction with a few oedometer tests, direct shear tests, drained (TXCD) and undrained (TXCU) triaxial tests to estimate the mechanical parameters of sediments. In addition, series of evaporation tests were performed for the estimation of the retention and hydraulic properties of riverbank soil in partially-saturated conditions. The geotechnical model discussed in this study refers in particular to section No. 3. The soil stratigraphy (Figure 2) was defined using well-established CPTU interpretation approaches (Tonni & Gottardi 2010; Robertson & Cabal 2015; Gottardi et al. 2015, Tonni et al. 2015). It includes a 5 m thick, rather heterogeneous, top layer of sands, silty sands and sandy silts (Unit R), forming the artificial river embankment; a predominantly silty unit (Unit B) from 5m to 12m depth, referable to the flood plain environment and corresponding to the upper part of the riverbank foundation subsoil; a clayey layer (Unit C) from 12m to 30m depth.

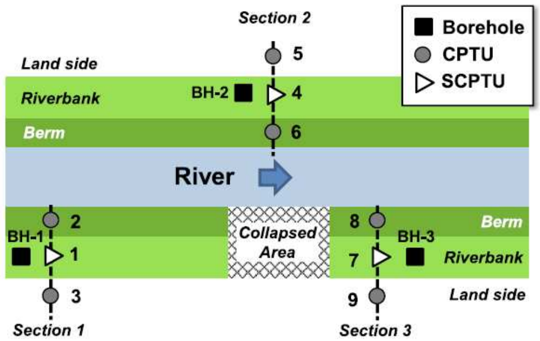

Figure 1. Sketch of the investigated area with location of boreholes, CPTU and SCPTU tests.

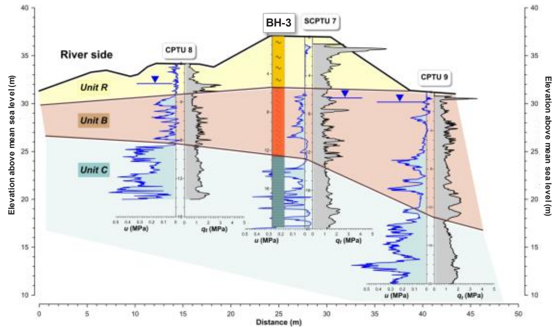

Figure 2. Stratigraphic model along cross-section N.3.

2.2 *Statistical characterization of soil properties*

For the probabilistic stability analysis, the unsaturated hydraulic parameters and the effective shear strength φ' of the only Unit R were statistically characterized. These variables were instead considered as deterministic values for the underlying soil units, i.e. Unit B and Unit C, the main goal being to investigate the effect of soil strength variability only within the river embankment. Furthermore, Unit B and Unit C are always fully saturated and thus not affected by partial saturation.

The hydraulic and retention response of Unit R was purposely studied by means of a series of evaporation tests, performed on nine undisturbed samples collected near Section No. 3, at depths between 0.7 m and 1.7 m from the crest. All tests were performed according to the parameter optimization procedure proposed by Romano and Santini (1999), with three repetitions for each sample. In this study, the well-known and widely-used hydraulic model proposed by van Genuchten (Van Genuchten 1980) was adopted to fit the experimental data:

$$S_e(h) = \frac{\theta - \theta_r}{\theta_0 - \theta_r} = \left[\frac{1}{1+(\alpha_{VG} \cdot s)^{n_{VG}}}\right]^{m_{VG}} \tag{1}$$

where S_e is the effective degree of saturation, θ, θ_0 and θ_r are the volumetric water content at the current stage, at saturation and in residual conditions respectively, s is the soil suction, α_{VG} and n_{VG} are model parameters, mainly influencing the inflection point and the slope of the retention curve. It is useful to mention that n_{VG} and m_{VG} are usually considered as inter-dependent parameters, defined as m_{VG} = 1-1/n_{VG}. In accordance with the Mualem's model (Mualem 1976) coupled with the parametrisation procedure suggested by van Genuchten, the variation of soil permeability with suction was derived from the Soil Water Retention Curve. Hence, the following equation was used:

$$k_r = S_e^{0.5}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{2}$$

The hydraulic permeability of the soil was then obtained as the product of the saturated permeability, k_0, and the relative permeability, k_r. Based on evaporation tests results, a statistical interpretation of the hydraulic parameters of Unit R was carried out, in terms of mean values, standard deviation, skewness (see Table 1) and correlation structure (see Table 2). Regarding Unit B and Unit C, only the permeability at saturation, k_0, was taken into account, since both units are permanently below the phreatic line. These parameters were considered as deterministic parameters in the probabilistic analyses and equal to the mean values obtained from the application of empirical correlations to piezocone data (Robertson & Cabal 2015). They turned out to be equal to $1.88\cdot10^{-6}$ m/s and $1.30\cdot10^{-9}$ m/s for Unit B and Unit C, respectively.

Table 1. Statistical characterization of the unsaturated hydraulic parameters of the river embankment soil Unit R

Parameters	*Mean value*	*Standard deviation*	*Skewness*
θ_r [m^3/m^3]	0.079	0.078	0.542
θ_{sat} [m^3/m^3]	0.395	0.041	0.026
α_{VG} [kPa^{-1}]	0.164	0.064	-0.824
n_{VG} [-]	1.328	0.154	0.016
log(k_0) [log(m/s)]	-5.805	0.776	-0.632

Table 2. Correlation matrix of the unsaturated hydraulic parameters of the river embankment soil Unit R

Parameters	θ_r	θ_{sat}	α_{VG}	n_{VG}	log(k_0)
θ_r	1.00	0.00	0.00	0.37	-0.51
θ_{sat}	-	1.00	0.34	0.69	0.63
α_{VG}	-	-	1.00	-0.09	0.68
n_{VG}	-	-	-	1.00	0.23
log(k_0)	-	-	-	-	1.00

The statistical information on the drained shear strength φ' was obtained from CPTU tests, applying well-established empirical correlations. In particular, for Unit R and Unit B, the effective friction angle at peak was determined using the well-known correlation proposed by Kulhawy and Mayne (1990). As regards the fine-grained Unit C, the estimates of φ' were instead obtained from an effective stress limit plasticity solution (Mayne & Campanella 2005) whose effectiveness was proved on a large database of natural clays (Ouyang & Mayne 2018). The statistical characterization of friction angle φ' of Unit R, obtained from CPTU tests interpretation, is presented in Table 3. The drained shear strengths of Unit B and Unit C, considered as deterministic parameters, were assumed equal to their mean values, namely 28.8° and 24.9° respectively.

Table 3. Statistical characterization of the friction angle φ' of the river embankment soil Unit R

Parameters	*Mean value*	*Standard deviation*	*Skewness*
φ' [°]	32.0	1.9	0.0

3 PROBABILISTIC STABILITY ANALYSIS OF THE RIVER EMBANKMENT

3.1 *Seepage model and stability analysis in transient conditions*

The probabilistic stability analysis of the river embankment was carried out with reference to a 2D model based on the geometry and stratigraphic conditions of section No. 3 of the River Secchia (Figure 2). The river embankment is 7 m high, with the outer (landward zone) and inner (riverside zone) slope angles equal to 30° and 33° respectively. The first step of analysis consisted in carrying out the seepage analysis thorough the embankment in transient conditions, accounting for the river level fluctuations, the rainfall infiltration and the partially saturated conditions of embankment soil Unit R. The transient unsaturated-saturated flow was modelled using the 2D Finite Element code SEEP/W (GEO-SLOPE international Ltd.), assuming the effective degree of saturation and the relevant hydraulic permeability derived from the application of the van Genuchten-Mualem model, as discussed in §2.2.

In order to start from realistic initial conditions, in the absence of specific measurements, the initial suction distribution into the bank was assumed to vary from a maximum value in the riverbank core to approximately zero at the free surface (Calabresi et al. 2013; Sleep and Duncan 2013;Rocchi et al., 2020). As a result, taking the water table at 30 m above the means sea level, close to the transition surface between Unit R and Unit B (see Figure 2), suction was assumed to linearly increase up to 39 kPa in correspondence of the centre of the bank, at 4 meters above the phreatic line, and then to decrease to zero close to the bank crest. Hydraulic boundary conditions were based on the river level measures and precipitation data recorded in close proximity to the investigated breached area, from 25 December 2013 to the flooding event date (19 January 2014). The positive and negative pore water pressure distributions obtained at the end of the seepage analysis (see Figure 3) were then imported into the code SLOPE/W (GEO-SLOPE international Ltd.) and assumed as input data for the river embankment stability calculations, with respect to the elapsed period of time. The Morgenstern and Price (1965) limit equilibrium method was adopted in the stability analyses.

The Vanapalli et al. (1996) soil shear strength criterion was used. This is expressed by the following analytical formulation:

$$\tau = c' + (\sigma_n - u_a)tan\varphi' + (u_a - u_w)S_e tan\varphi' \quad (3)$$

where σ_n is the total normal stress, c' is the effective cohesion, φ' is the effective stress friction angle. The first part of the equation describes the shear strength contribution due to the normal net stress; the second part provides the shear strength contribution due to suction, which can be predicted using the soil water retention curve. As a result, the shear strength of an unsaturated soil is assumed to vary with the degree of saturation S_e and the matric suction ($u_a - u_w$) as long as the soil is partially saturated. The shear strength parameters c' and φ' are assumed as constant and equivalent to the saturated state values.

As regards the stability analyses, both the inner and outer slopes of the river embankment were investigated. The slip surfaces were generated according to suitable pre-defined geometrical constraints, which consisted in specifying a range for the entry zone and the exit zone of the sliding mechanism on the ground surface, together with the minimum depth of the slices height. The latter constraint was meant to identify only significant collapse mechanisms, while neglecting local, insignificant shallow slip surfaces. The minimum slip surface depth was assumed to be 1.5 m and 3.8 m for the inner and outer instability mechanisms, respectively. Typical slip surfaces investigated in the stability analyses are shown in Figure 4.

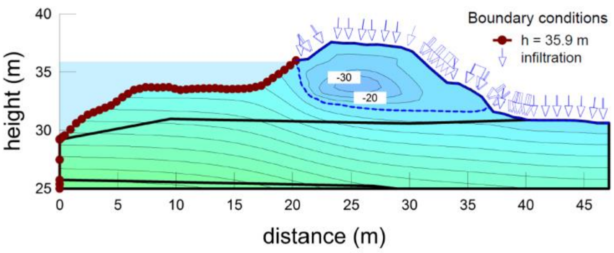

Figure 3. Pore water pressure distribution at the end of transient seepage analysis.

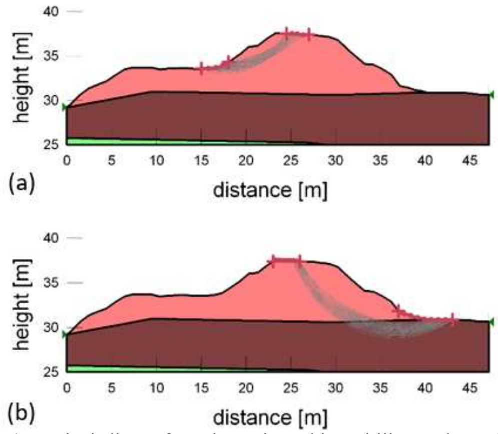

Figure 4. Typical slip surfaces investigated in stability analyses for inner (a) and outer (b) slopes.

3.2 *Probabilistic analysis and results*

As known, a probabilistic analysis consists in propagating the uncertainty from input data (e.g. mechanical properties, retention and hydraulic soil parameters) to the final result (e.g. the stability safety factor).

In geotechnical practice and research, both simplified and more accurate uncertainty propagation methods have been successfully adopted. Simplified methods, like First Order Second Moment Method (FOSM), Point Estimate Method (PEM) or First Order Reliability Method (FORM) (Duncan 2000; Baecher and Christian 2003; Vannucchi et al. 2014), allow to easily apply the uncertainty propagation to the slope stability analyses based on the Limit Equilibrium or Finite Element methods. Instead, the more accurate methods, like Monte Carlo Method (MCM) and Subset Simulation method, turn out to be more difficult to be implemented and very time-consuming, so that their use in routine engineering practice is still far from being routinely adopted. For these reasons, the simplified methods provide a valid, efficient and relatively easy tool to incorporate spatial variability of soil properties into reliability analysis and risk assessment of slope stability, especially when failure probability is not very low. In this case, indeed, such methods typically result in an approximate but not erroneous estimate of the probability of failure.

In this work, the Point Estimate Method (Panchalingam & Harr 1994) was used as probabilistic procedure to propagate the uncertainty from the geotechnical and hydraulic soil properties to the stability safety factor of the river embankment. The method consists in replacing the continuous random variables, characterized by a probability density function, with discrete random variables, each described by two points with assigned weight. The discrete points and the relevant weights are estimated on the basis of the statistical moments of the continuous random variables, i.e. mean value, variance, skewness coefficient and the correlation matrix. For a function of N random variables, the method provides 2^N discrete points combinations. For each parameters combination the stability safety factor is evaluated deterministically, performing at first the seepage analysis in transient condition and then the stability analysis with randomly generated slip surfaces. The values of safety factors thus calculated are then combined on the basis of the weight assigned to each parameter combination, in order to obtain the mean μ_{SF} and the standard deviation σ_{SF} of the safety factor SF. The reliability index β and the probability of failure P_f are then estimated as follows:

$$\beta = \frac{\mu_{SF}-1}{\sigma_{SF}} \quad (4)$$

$$P_f = 1 - \Phi(\beta) \quad (5)$$

where Φ is the cumulative distribution of the standard normal random variable. A Normal probability distribution of the safety factor is then assumed in order to obtain the probability of failure. More details on the procedure can be found in Gottardi et al. (2020).

In this study, in order to investigate the effect of multiple sources of uncertainties in soil parameters (i.e. both shear strength and unsaturated hydraulic properties) on the probability of failure of the river embankment, in terms of overall stability, two sets of probabilistic analyses were performed and compared:

Case 1: effective shear strength φ' of Unit R as random variable, hydraulic parameters θ_r, θ_0, α_{VG}, n_{VG}, k_0, as deterministic variables, equal to their mean values.

Case 2: effective shear strength φ' of Unit R as random variable, hydraulic parameters θ_r, θ_0, α_{VG}, n_{VG}, k_0, as correlated random variables. Unlike Case 1, Case 2 involves the variability of all hydraulic parameters, including all the available statistical information.

As a result, the PEM application required no. 2 parameter combinations for Case 1 and no. 64 parameters combinations for Case 2.

The results of the probabilistic analyses are presented in Table 4 and Table 5, for both cases, in terms of mean value and standard deviation of the safety factor, reliability index and probability of failure.

Table 4 – Comparison of probabilistic results of the limit equilibrium analyses in transient seepage condition for the river embankment inner slope, for Case 1 and Case 2

Probabilistic Analysis Results – Inner slope		
Safety Factor	Case 1	Case 2
Mean (μ_{SF})	2.077	2.064
Standard deviation (σ_{SF})	0.156	0.338
Reliability index (β_{SF})	6.904	3.145
Probability of failure (P_f, %)	$< 10^{-3}$	0.08

Table 5 – Comparison of probabilistic results of the limit equilibrium analyses in transient seepage condition for the river embankment outer slope, for Case 1 and Case 2

Probabilistic Analysis Results – Outer slope		
Safety Factor	Case 1	Case 2
Mean (μ_{SF})	1.346	1.328
Standard deviation (σ_{SF})	0.063	0.119
Reliability index (β_{SF})	5.492	2.745
Probability of failure (P_f, %)	$< 10^{-3}$	0.30

The results show that the mean value of the safety factor is approximately equal to 1.3 for the outer slope and close to 2.0 for the inner slope, with minor differences between the two cases mentioned above. In general, it is immediate to observe that the riverside zone appears to be significantly more stable than the landward zone. Furthermore, in a deterministic standard approach, the values of the safety factor turn out to be sufficiently high. In fact, it is worth mentioning that other possible local structural weaknesses, such as the extensive presence of animal burrows, were advocated as the most probable causes of the sudden failure occurred in January 2014. Independently of the actual factors that triggered the collapse in 2014, this probabilistic study is meant to identify the significant differences in the evaluation of the river embankment reliability, as a consequence of different uncertainty sources assumptions.

In this respect, although the mean values of the safety factor in Case 1 and Case 2 are very similar, the standard deviations of the safety factor relative to Case 2 are approximately 2 times greater than those obtained for Case 1 (the ratio is about 4 times in terms of variance). This leads to a reduction of the reliability index of about the same order of magnitude, i.e. 2 times.

In other words, accounting for the variability of hydraulic parameters in addition to shear strength, the uncertainty degree in the estimate of the safety factor increases considerably, with associated rather low values of the reliability index. Accordingly, the probability of failure turns out to be non-negligible, namely higher that 10^{-1}-10^{-2}%, for both the inner and outer slope, whilst extremely low values of P_f (< 10^{-3}%) were obtained when the only source of uncertainty was assumed to lie in shear strength (Case 1).The probability density functions plotted in Figure 5 and Figure 6 provide clear evidence of the increase of the standard deviation of the safety factor when the stability analyses were carried out under stochastic unsaturated transient seepage conditions. The effect may be appreciated in both riverbank slopes, being the shape of the probability distribution associated with Case 2 significantly wider than the "thin" shape of Case 1.

In order to quantitatively evaluate the relative importance of the shear strength parameter and the hydraulic parameters on the safety factor uncertainty, the percentage contribution of the effective friction angle $\sigma^2_{\varphi'}(\%)$ and the hydraulic parameters $\sigma^2_{hp}(\%)$ to the safety factor variance was calculated as follows:

$$\sigma^2_{\varphi'}(\%) = 100 \cdot \sigma^2_{SF,C1} / \sigma^2_{SF,C2} \quad (6)$$

$$\sigma^2_{hp}(\%) = 100 \cdot \left(\sigma^2_{SF,C2} - \sigma^2_{SF,C1}\right) / \sigma^2_{SF,C2} \quad (7)$$

Then the contribution of the hydraulic parameters to the safety factor variance σ^2_{SF} was calculated as the difference between the safety factor variance computed in Case 2 $\sigma^2_{SF,C2}$ and the safety factor variance associated with Case 1 $\sigma^2_{SF,C1}$, the latter being based on the uncertainty in shear strength φ' only.

According to the results plotted in Figure 7, the hydraulic parameters appear to have the largest influence on the uncertainty of the safety factor, with percentages of contribution equal to 72% and 79% for the outer slope and inner slope respectively. These results demonstrate that for usual values of the uncertainty degree of the effective friction angle (in this case the coefficient of variation of φ' is about 6%) (Lacasse & Nadim 1996; Phoon & Kulhawy 1999; Baecher & Christian 2003) the variability of the unsaturated soil hydraulic parameters plays a crucial role in the assessment of the probability of failure of river embankment in terms of the overall stability.

Hence, neglecting the intrinsic variability of such parameters may lead to a not conservative estimate of the probability of failure, even in soils assumed as relatively homogeneous from a geotechnical point of view.

4 CONCLUSIONS

This paper has presented a probabilistic study aimed at investigating the role of the hydraulic parameters, which govern the partial saturation behaviour of soil, on the stability condition of an existing river embankment.

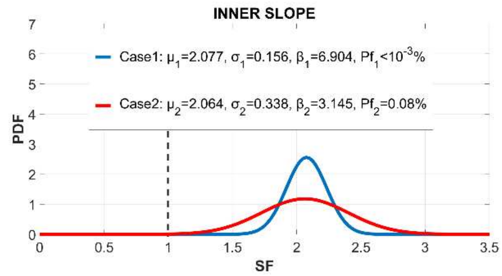

Figure 5. Probability density function (PDF) of the safety factor (SF) for the inner slope, in the Case 1 and Case 2.

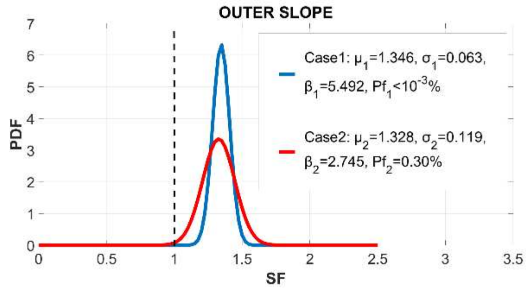

Figure 6. Probability density function (PDF) of the safety factor (SF) for the outer slope, in the Case 1 and Case 2.

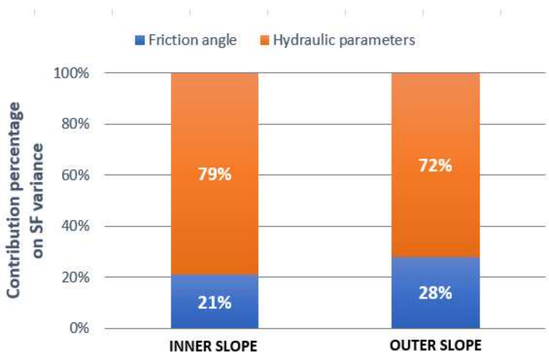

Figure 7. Contribution of the friction angle and hydraulic parameters on the safety factor variance, for the inner and outer slope.

A fully probabilistic analysis is the only way at the moment to take into account the uncertainty of the both soil strength parameters and hydraulic parameters. As a matter of fact, the semi-probabilistic approaches, provided by international standard codes, allow applying partial safety factors only to the soil strength, being impossible to define a priori the favourable or unfavourable contribution of the hydraulic parameters towards the overall stability of river embankments. Assuming the latter parameters as deterministic can lead to a significant underestimation of the actual margin of safety.

To this purpose, a deeply-investigated river embankment in northern Italy, which experienced a sudden collapse after a period of intense rainfall, was taken as reference for series of reliability analyses. The large and varied geotechnical database collected for this case study enabled the development of a detailed geotechnical model of the breached segment, in terms of both mechanical and hydraulic characterization of the sediments forming the unsaturated riverbank.

In this study, a transient seepage analysis of the river embankment was first modelled, accounting for the time-dependent hydraulic boundary conditions, due to water level fluctuations in the river, and the unsaturated initial state of the embankment. Then, considering the positive and negative pore water pressure distributions obtained at the end of the seepage modelling, stability analyses were performed, using limit equilibrium method.

The uncertainty propagation from hydraulic and shear strength parameters to the stability safety factor of the river embankment was performed using the Point Estimate Method. This is a widely recognized procedure which appears to offer significant advantages in terms of efficiency compared to more robust methods, e.g. the Monte Carlo method, where the assessment of the probability of failure can be computationally very demanding, especially when applied to finite element and limit equilibrium analyses. Furthermore, simplified methods like Point Estimate Method provide a sufficient degree of accuracy particularly in exploring the relative weight of the different random variables on the probability of failure.

Although the actual safety factors of both inner and outer slopes of the investigated river embankment turned out to be generally well above unity, suggesting that the January 2014 failure was probably due to lack of local integrity for animal burrows, results presented in this paper have proved that the probability of failure is strongly influenced by the suction distribution, which in turn depends on the hydraulic parameters adopted in the analyses. Indeed, when uncertainty in unsaturated hydraulic parameters was taken into account, the probability of failure turned out to be significantly higher than that obtained on the assumption that shear strength was the only random variable. The difference in this case was found to be of various orders of magnitude. These results imply that, for the usual uncertainty degree of shear strength, the variability of the unsaturated soil hydraulic parameters has a major impact on the resulting uncertainty of the stability safety factor.

As a result, neglecting the effect of the intrinsic variability of hydraulic parameters, even in soils assumed as relatively homogenous, may lead to values of probability of failure non-conservative and thus not consistent with the actual risk level of the river embankment.

6 REFERENCES

Amabile A., De Polo F. and Tarantino A. 2020. Probabilistic analysis of flood embankment stability: the case study of the Adige River embankment in Italy. *Proc. 4th European Conference on Unsaturated Soils*, Lisbon, Portugal, 195, 01003.

Baecher G.B. and Christian J.T. 2003. Reliability and Statistics in Geotechnical Engineering. *Wiley edition*.

Calabresi G., Colleselli F., Danese D., Giani G., Mancuso C. and Montrasio L. 2013. Research study of the hydraulic behaviour of the Po River embankments. *Canadian Geotechnical Journal* 50, 947–960.

Cho S.E. 2012. Probabilistic analysis of seepage that considers the spatial variability of permeability for an embankment on soil foundation. *Engineering Geology* 133–134, 30–9.

Duncan J.M. 2000. Factors of Safety and Reliability in Geotechnical Engineering. *Journal of Geotechnical and Geoenvironmental Engineering* 126, 307–16.

Gottardi G., Marchi M. and Tonni L. 2015. Static stability of Po river banks on a wide area. *Proc. 16th European Conference on Soil Mechanics and Geotechnical Engineering*, Edinburgh, UK 1675-1680.

Gottardi G. and Gragnano C.G. 2016. On the role of partially saturated soil strength in the stability analysis of a river embankment under steady-state and transient seepage conditions. *Proc. 3th European Conference on Unsaturated Soils*, Paris, France, 9, 19002.

Gottardi G., Gragnano C.G., Ranalli M. and Tonni L. 2020. Reliability analysis of riverbank stability accounting for the intrinsic variability of unsaturated soil parameters. *Structural Safety* 86(2020) 101973.

Kulhawy F.H. and Mayne P.W. 1990. Manual on Estimating Soil Properties for Foundation Design.

Lacasse S. and Nadim F. 1996. Uncertainties in characterising soil properties. *Publication - Norges Geotekniske Institutt* 201:49–75.

Liang C., Jaksa M.B., Ostendorf B. and Kuo Y.L. 2015. Influence of river level fluctuations and climate on riverbank stability. *Computer and Geotechnics* 63, 83–98.

Mayne P.W. and Campanella R.G. 2005. Versatile site characterization by seismic piezocone. *16th International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, Japan: 721–724.

Morgenstern N.R. and Price V.E. 1965. Analysis of the stability of general slip surfaces. *Géotechnique* 15(1), 79–93.

Mualem Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* 12, 513–522.

Ouyang Z. and Mayne P.W. 2018. Effective friction angle of clays and silts from piezocone penetration tests. *Canadian Geotechnical Journal* 55, 1230–1247

Panchalingam G. and Harr M.E. 1994. Modelling of many correlated and skewed random variables. *Applied Mathematical Modelling* 18, 635–40.

Phoon K.-K. and Kulhawy F.H. 1999. Characterization of geotechnical variability. *Canadian Geotechnical Journal* 36, 612–624.

Phoon K.-K., Santoso A. and Quek S.-T. 2010. Probabilistic Analysis of Soil-Water Characteristic Curves. *Journal of Geotechnical and Geoenvironmental Engineering* 136, 445–55.

Ranalli M., Medina-Cetina Z., Gottardi G. and Nadim F. 2014. Probabilistic calibration of a dynamic model for predicting rainfall-controlled landslides. *Journal of Geotechnical and Geoenvironmental Engineering* 140(4), 4013039.

Rinaldi M., Casagli N., Dapporto S. and Gargini A. 2004. Monitoring and modelling of pore water pressure changes and riverbank stability during flow events. *Earth Surf Process Landforms* 29(2), 237–54.

Rocchi I., Gragnano C.G., Govoni L., Bittelli M. and Gottardi G. 2020. Assessing the performance of a versatile and affordable geotechnical monitoring system for river embankments. *Physics and Chemistry of the Earth* 117, 102872.

Robertson P.K. and Cabal K.L. 2015. Guide to cone penetration testing for geotechnical engineering. *Gregg Drilling & Testing*, California, United States.

Romano N. and Santini A. 1999. Determining soil hydraulic functions from evaporation experiments by a parameter estimation approach: Experimental verifications and numerical studies. *Water Resources Research* 35, 3343–3359.

Santoso A., Phoon K.K. and Quek S.T. 2011. Effects of soil spatial variability on rainfall-induced landslides. *Computers and Structures* 89(11–12), 893-900.

Schweiger H.F., Thurner R. and Pöttler R. 2011. Reliability Analysis in Geotechnics with Deterministic Finite Elements. *International Journal of Geomechanics* 1, 389–413.

Sleep M.D. and Duncan J.M. 2013. Effects of initial conditions on the results of transient seepage analyses. *Proc. Geo-Congress 2013 Stab. Perform. Slopes Embankments III*, San Diego, California, US, 1081–1091.

Tonni L. and Gottardi G. 2010. Interpretation of piezocone tests in Venetian silty soils and the issue of partial drainage. *Deep foundations and geotechnical in situ testing*, ASCE Geotechnical Special Publication No. 178. Reston, Virginia, US, 367-374.

Tonni L, Gottardi G, Amoroso S, Bardotti R, Bonzi L, Chiaradonna A, et al. 2015. Interpreting the deformation phenomena triggered by the 2012 Emilia seismic sequence on the Canale Diversivo di Burana banks. *Rivista Italiana di Geotecnica* 49(2), 28–58.

Van Genuchten M.T. 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal* 44, 892.

Vanapalli S.K., Fredlund D.G., Pufahl D.E. and Clifton A.W. 1996. Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal* 33, 379–392.

Vannucchi G., Gottardi G., Madiai C., Marchi M. and Tonni L. 2014. Analisi della probabilità di collasso arginale dei grandi fiumi. *XXV National Geotechnical Conference*, Baveno, Italy, 303–319.

Zhang L., Li J., Li X., Zhang J. and Zhu H. 2019. Rainfall-Induced Soil Slope Failure: Stability Analysis and Probabilistic Assessment. CRC Press, Taylor & Francis Ltd, London, United Kingdom.