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Reliability analysis of riverbank stability accounting for the intrinsic variability of unsaturated soil parameters

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

Reliability analysis of riverbank stability accounting for the intrinsic variability of unsaturated soil parameters / Guido Gottardi, Carmine G. Gragnano, Marco Ranalli, Laura Tonni. - In: STRUCTURAL SAFETY. - ISSN 0167-4730. - ELETTRONICO. - 86:September 2020(2020), pp. 101973.1-101973.13. [10.1016/j.strusafe.2020.101973]

*Availability:*

This version is available at: <https://hdl.handle.net/11585/760427> since: 2020-06-30

*Published:*

DOI: <http://doi.org/10.1016/j.strusafe.2020.101973>

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**Guido Gottardi, Carmine G. Gragnano, Marco Ranalli, Laura Tonni, Reliability analysis of riverbank stability accounting for the intrinsic variability of unsaturated soil parameters, *Structural Safety*, Volume 86, 2020, 101973, ISSN 0167-4730.**

The final published version is available online at:

<https://doi.org/10.1016/j.strusafe.2020.101973>

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*Article Title:*

## **Reliability analysis of riverbank stability accounting for the intrinsic variability of unsaturated soil parameters**

*Journal Name:*

**Structural Safety**

*Authors:*

**Guido Gottardi<sup>a,\*</sup>, Carmine G. Gragnano<sup>b</sup>, Marco Ranalli<sup>c</sup>, Laura Tonni<sup>d</sup>**

<sup>a,\*</sup>Corresponding Author, *Department of Civil, Chemical, Environmental and Materials Engineering, DICAM, Alma Mater Studiorum - University of Bologna. Viale Risorgimento 2, 40136 Bologna (Italy). Phone: +39 0512093524.*

E-mail: [guido.gottardi2@unibo.it](mailto:guido.gottardi2@unibo.it)

<sup>b</sup>*Department of Civil, Chemical, Environmental and Materials Engineering, DICAM, Alma Mater Studiorum - University of Bologna. Viale Risorgimento 2, 40136 Bologna (Italy).*

E-mail: [carmine.gragnano2@unibo.it](mailto:carmine.gragnano2@unibo.it)

<sup>c</sup>*Department of Civil, Chemical, Environmental and Materials Engineering, DICAM, Alma Mater Studiorum - University of Bologna. Viale Risorgimento 2, 40136 Bologna (Italy).*

E-mail: [marco.ranalli@unibo.it](mailto:marco.ranalli@unibo.it)

<sup>d</sup>*Department of Civil, Chemical, Environmental and Materials Engineering, DICAM, Alma Mater Studiorum - University of Bologna. Viale Risorgimento 2, 40136 Bologna (Italy).*

E-mail: [laura.tonni@unibo.it](mailto:laura.tonni@unibo.it)

ORCID 0000-0002-9391-6661

## 1 **Abstract**

2 The paper presents a probabilistic study aimed at investigating the role of the soil hydraulic  
3 response on the stability of existing river embankments, for which the uncertainty and the inherent  
4 variability of geotechnical and hydraulic properties are typically greater when compared to new  
5 flood defence structures. The study has been carried out with reference to a specific, thoroughly  
6 investigated 20 m-long segment of the river Secchia banks (northern Italy), which experienced a  
7 catastrophic sudden failure after a period of intense rainfall, in January 2014. By taking such well-  
8 documented case as a base, the proposed probabilistic analyses consider three key aspects, typically  
9 disregarded in routine risk assessment procedures: i) transient seepage flow through earth structures  
10 due to time dependent hydraulic loads, ii) unsaturated conditions of soils forming the river  
11 embankment, iii) uncertainty of the soil model parameters, with special emphasis placed on the  
12 impact of intrinsic variability of unsaturated soil parameters. The numerical results, obtained from  
13 the application of the *Point Estimate Method*, allow identifying the crucial role of suction  
14 distribution on the probability of failure of the riverbank slopes and clearly show that such  
15 probability can be significantly underestimated when the variability of hydraulic parameters is  
16 neglected.

17

18 **Keywords:** unsaturated soil, transient seepage, probabilistic analysis, Point Estimate Method,  
19 riverbank stability

## 1. Introduction

The evaluation of riverbank stability represents a fundamental task in georisk assessment. Indeed, overestimating the safety margin of a flood defence structure may potentially lead to totally unexpected failures and subsequent severe consequences in terms of damages, repairing costs and human losses. Hence, a thorough understanding of the different factors adversely affecting riverbank stability and the way they interact to determine failure conditions is a necessary step for engineers in order to design successful and cost-effective countermeasures against potential collapses.

In recent years, the use of numerical methods has offered a powerful means to develop accurate groundwater seepage models, enabling transient analyses coupled with unsaturated stress approaches for the evaluation of the dynamic distribution of pore water pressure due to rainfall events, evaporation and river level fluctuations. A number of studies ([1-2] among others), based on different numerical approaches, have thus investigated in great detail the effect of changes in pore water pressures on the riverbank stability, with special attention paid to the crucial role of matric suction and its influence on the soil properties in the partially saturated zone of the embankment.

At the same time, numerical analysis has proved to be a suitable and effective tool in order to take into account a further fundamental geotechnical issue, that is the intrinsic variability of soils properties, even in relatively homogeneous deposits, together with the unavoidable uncertainties due to limited experimental data and to the related correlation models adopted for soil characterization [3-8].

A large number of research contributions (e.g. [9-14]), based on either theoretical applications or failure case studies, have discussed the effect of uncertainties and spatial variation of soil shear strength on slope analysis reliability, whilst only few available studies have also considered the variability of hydraulic properties, particularly those governing the behaviour of unsaturated soils [15-16]. An even more limited number of published works [17] have actually tackled the problem with reference to existing river embankments and a substantial lack of applications to relevant case

46 studies is thus observed. However, in these structures the spatial variability of hydraulic properties,  
47 especially in unsaturated soil conditions, may remarkably affect both the seepage regime [18-19],  
48 which results in specific flow paths, and the unsaturated soil shear strength [20], with significant  
49 implications on the overall stability.

50 In order to gain a better insight into such geotechnical issues, this paper presents an extensive  
51 probabilistic study specifically aimed at investigating the role of the intrinsic variability of  
52 unsaturated soil hydraulic properties in the assessment of existing riverbank safety conditions. The  
53 study has been carried out using the geotechnical dataset collected along a 20 m bank segment of  
54 the Secchia river, a right tributary of the major Po river, north of the historic town of Modena  
55 (Italy). Following the catastrophic failure occurred in January 2014 [21], this river embankment  
56 segment was thoroughly investigated by means of in situ and laboratory tests and a valuable and  
57 varied database has thus become available for the analyses. Starting from such well-documented  
58 real case, the objective of the study is primarily to examine the effect of different geotechnical  
59 sources of uncertainties on riverbank stability, with specific emphasis on the crucial impact of  
60 intrinsic variability of unsaturated soil hydraulic parameters. After a brief summary of the *Point*  
61 *Estimate Method* (PEM), which is the probabilistic approach adopted in this numerical study, and of  
62 the accurate geotechnical characterization of the sediments forming the whole river embankment  
63 system, the paper first presents the results of a few preliminary limit equilibrium analyses under  
64 steady-state seepage conditions, assuming soil shear strength as the only source of uncertainty.  
65 Next, two further series of limit equilibrium analyses, performed under transient flow conditions as  
66 induced by fluctuating river levels and rainfall events, are shown and the effect of assuming  
67 hydraulic parameters either as deterministic or random variables is discussed with respect to the  
68 resulting probability of riverbank failure. As regards the specific collapse that led to the January  
69 2014 large breach in the Secchia river embankment, it is worth observing that in such case the  
70 triggering mechanism was eventually ascribed to a potential local lack of structural integrity  
71 induced by animal burrows [21], which is outside the scope of this study and therefore it will not be

72 considered in the following analyses. However, the localised damages observed in the surroundings  
73 of the failed section, coupled with the reduction in saturation degree and suction caused by  
74 persistent and ever increasing high water events, have shown the need to further explore the actual  
75 factors affecting the potential riverbank instability and to provide a rational methodological  
76 approach to take into account the unavoidable intrinsic variability of the soil parameters which  
77 control the local conditions.

78

## 79 **2. Uncertainty propagation methods**

80 The uncertainty propagation analysis allows propagating the errors from input data (e.g. mechanical  
81 properties, retention and hydraulic soil parameters) to the final result (i.e. the factor of safety and  
82 the probability of failure in ultimate limit state analyses). In geotechnical practice and research, a  
83 number of simplified uncertainty propagation methods, like *First Order Second Moment Method*  
84 (FOSM), *Point Estimate Method* (PEM) or *First Order Reliability Method* (FORM) have long been  
85 successfully adopted (e.g. [9,22-25]). Such approaches are often used as a valid alternative to more  
86 accurate and well-established procedures, typically the *Monte Carlo Method* (MCM), which turn  
87 out to be more difficult to be implemented and very time-consuming when adopted in slope stability  
88 analyses based on Limit Equilibrium or Finite Element methods [25]. In addition to the simplified  
89 FOSM, PEM and FORM mentioned above, in recent years advanced stochastic approaches, capable  
90 of combining accuracy with computational efficiency, have been also proposed in the literature with  
91 the aim of overcoming the prohibitive time and resources efforts required by the direct MCM.  
92 Among them, it is worth mentioning the *Stochastic Response Surface Method* [26] and, in  
93 particular, the *Subset Simulation* [27-29]. However, although these latest computational strategies  
94 have been devised to alleviate and facilitate the application of probability-based approaches in slope  
95 assessment, their use in routine engineering practice is still far from being widespread, probably due  
96 to complexity of the relevant implementation algorithms. Some authors (e.g. [28]) also observed  
97 that *Subset Simulation* still requires a significant computational cost at extremely small probability

98 levels (e.g., probability of failure  $P_f < 10^{-4} \sim 10^{-5}$ ).

99 At the same time the simplified methods, though approximated, appear to provide a valid, efficient  
100 and relatively easy tool to incorporate spatial variability of soil properties into reliability analysis  
101 and risk assessment of slope stability, especially when failure probability is not very low. In this  
102 case, indeed, such methods typically result in an approximate but not erroneous estimate of the  
103 probability of failure. Regarding this point, it is worth observing also that the accuracy of the  
104 computed probability of failure largely depends on the reliability of the statistical characterization  
105 of the input parameters, and that the estimates of the probability of failure should be interpreted in  
106 terms of their order of magnitude, as emphasized by Duncan and Sleep [30].

107 In this work, the *Point Estimate Method* in particular was used as probabilistic procedure to  
108 propagate the uncertainty from the geotechnical and hydraulic soil properties to the probability of  
109 failure ( $P_f$ ) of the riverbank slopes. Computational efficiency, together with a rather straightforward  
110 implementation procedure, caused PEM to be selected instead of MCM. In spite of a certain  
111 “roughness” of the adopted method, a few preliminary analyses, carried out with both PEM and  
112 MCM and accounting for the only uncertainties on soil shear strength, led to numerically different  
113 results, lying however in the same order of magnitude. This outcome, obtained for values of  $P_f$   
114 relatively high, cannot be obviously considered as generally valid.

115 The *Point Estimate Method* is widely used when no closed-form analytical solutions are available  
116 and a number of successful applications of the method [31-33] to typical geotechnical stability  
117 problems, either using Limit Equilibrium Method (LEM) or the Finite Element Method (FEM), can  
118 be found in the literature. Furthermore, in recent years the PEM has been implemented in a number  
119 of commercial codes that are commonly used for stability analyses, hence its use is very likely to  
120 earn popularity among engineers also for routine applications.

121

## 122 **2.1 Adopted probabilistic approach**



123 The *Point Estimate Method* consists in replacing the continuous random variables, characterized by  
124 a probability density function, with discrete random variables described by two or more points with  
125 assigned weight. The discrete points and the relevant weights are estimated on the basis of the  
126 statistical moments of the continuous random variables, i.e. mean value, variance and skewness  
127 coefficient.

128 The original PEM [34-36] allowed considering such first three statistical moments only in case of  
129 function of a single random variable; in case of multiple variables, the application of the method  
130 was restricted to systems of correlated and symmetrically distributed random variables. The later  
131 formulation developed by Panchalingam and Harr [37] allowed incorporating both correlated and  
132 skewed random variables into the uncertainty analysis in the case of multivariate random variables  
133 problems as well. The key features of the method are briefly summarized below.

134 Let  $f(X) = f(X_1, X_2, \dots, X_N)$  be a function of  $N$  correlated and skewed random variables. The first  
135 three statistical moments (mean, standard deviation and skewness coefficient) and the correlation  
136 structure of random variables are assumed to be known.

137 The method firstly defines the point estimate locations through the statistical moments of the  
138 random variables. For each random variable, two point estimate locations are evaluated, according  
139 to the following relationships:

$$140 \quad (1) \quad X_+ = \mu_X + \left[ \frac{v_X}{2} + \sqrt{1 + \left(\frac{v_X}{2}\right)^2} \right] \sigma_X$$

$$141 \quad (2) \quad X_- = \mu_X + \left[ \frac{v_X}{2} - \sqrt{1 + \left(\frac{v_X}{2}\right)^2} \right] \sigma_X$$

142 where  $\mu_X$  is the mean value,  $\sigma_X$  is the standard deviation and  $v_X$  is the skewness coefficient.

143 Estimate locations  $X_+$  and  $X_-$  are then associated with weights  $P_+$  and  $P_-$  respectively. These are  
144 given by:

$$145 \quad (3) \quad P_+ = \frac{1}{2} \left[ 1 - \frac{v_X}{2} \frac{1}{\sqrt{1 + (v_X/2)^2}} \right]$$

$$146 \quad (4) \quad P_- = 1 - P_+$$

147 For a function of  $N$  random variables, the method provides  $2^N$  point estimate locations, resulting  
 148 from all possible combinations of point estimate locations. Accordingly, the weight associated with  
 149 a general combination  $(X_{1\pm}, X_{2\pm}, \dots, X_{N\pm})$  is defined as:

$$150 \quad (5) \quad P_{\pm\pm\pm\pm} = P_{1\pm}P_{2\pm} \dots P_{N\pm} + \sum_{i=1}^{N-1} \sum_{j=i+1}^N (\pm)_i (\pm)_j a_{ij} P_{ij}$$

151 where  $a_{ij} = \rho_{ij} (P_{i+}P_iP_{j+}P_j)^{0.5}$ ,  $\rho_{ij}$  = correlation coefficient between the random variables  $X_i$  and  $X_j$ ,  
 152  $P_{ij} = P_{1\pm}P_{2\pm}\dots P_{k\pm}\dots P_{N\pm}$  ( $k \neq i$  and  $k \neq j$ ).

153 The statistical  $m$ -th moment of the function  $f(X)$  can be therefore expressed as follows:

$$154 \quad (6) \quad E[f(x)^m] \approx \sum_{j=1}^k P_j f(X_j)^m$$

155 where  $k$  is the number of point estimate locations,  $P_j$  is the weight associated with combination  $j$ ,  
 156  $f(X_j)$  is the function evaluated at point estimate location  $j$ . In particular, the mean  $\mu_{f(X)}$  and the  
 157 variance  $\sigma_{f(X)}^2$  of the function can be then estimated according to the following relationships:

$$158 \quad (7) \quad \mu_{f(X)} = E[f(x)]$$

$$159 \quad (8) \quad \sigma_{f(X)}^2 = E[f(X)^2] - (E[f(x)])^2$$

160 Finally, the reliability index  $\beta$  and the probability of failure  $P_f$  are given by:

$$161 \quad (9) \quad \beta = \frac{\mu_{SF}-1}{\sigma_{SF}}$$

$$162 \quad (10) \quad P_f = 1 - \Phi(\beta)$$

163 where  $\Phi$  is the cumulative distribution of the standard normal random variable. A Normal  
 164 probability distribution of the safety factor is assumed in order to obtain the probability of failure.

165

### 166 **3. Reference case study**

167 The probabilistic study proposed in this paper was carried out with reference to a specific,  
 168 thoroughly investigated 20 m-long segment of the river Secchia banks (northern Italy), which  
 169 suddenly collapsed after a period of intense rainfall, in January 2014 (Figure 1). This section

170 provides a brief description of the detailed and rather varied geotechnical database collected after  
171 the bank failure in order to obtain information related to the collapse and used as reference dataset  
172 for the analyses contained herein.

173 As shown in Figure 2, the site investigation campaign was carried out along three main  
174 representative alignments: the first alignment was selected upstream from the collapsed river  
175 embankment section, approximately 900 m distant from the breach, the second was located in front  
176 of the collapsed area, on the opposite river embankment, whilst the third was placed next to the  
177 breach, only a few meters away on the downriver side. For each alignment, a borehole (BH) and a  
178 seismic piezocone test (SCPTU) were carried out from the crest of the river embankment and  
179 pushed to approximately 30 m in depth; two additional piezocone tests (CPTU) were carried out at  
180 the berm and close to the outer slope toe. The latter tests were stopped at different depths, from 14  
181 to 26 m, depending on their position on the river embankment. A few dissipation tests were also  
182 carried out along each piezocone vertical, in order to monitor the pore water pressure decay with  
183 time and to evaluate the consolidation characteristics of fine sediments.

184 The laboratory experimental programme, carried out on a total of 27 undisturbed soil samples,  
185 included a significant number of tests for the determination of basic physical properties of soils,  
186 Atterberg limits, particle size distribution, in conjunction with a few oedometer tests, direct shear  
187 tests, drained (TXCD) and undrained (TXCU) triaxial tests to estimate the mechanical parameters  
188 of sediments. In addition, series of evaporation tests were performed for the estimation of the  
189 retention and hydraulic properties of the river embankment soil in partially-saturated conditions.

190

### 191 **3.1 In situ testing interpretation**

192 The subsoil beneath the collapsed river embankment stretch mainly consists of Pleistocene alluvial  
193 sediments resulting from depositional and erosional process of the Secchia and Panaro rivers, both  
194 draining a significant part of the Emilian Apennines into the major Italian watercourse Po.

195 Figure 3 shows the profiles of the corrected cone resistance  $q_t$ , sleeve friction  $f_s$  and pore pressure  $u$

196 obtained from the representative piezocone test SCPTU 7, located on the river embankment crest in  
197 Section No. 3, the latter being depicted here according to its geometry after collapse. The  
198 interpretation of piezocone data in terms of the well-known classification framework proposed by  
199 Robertson [38], aimed at identifying the in situ Soil Behaviour Type (*SBT*), and the actual soil  
200 stratigraphy provided by the adjacent borehole BH-3 are also reported in the figure. Despite a few  
201 discrepancies observed between CPTU-based classification results and the stratigraphy from  
202 boreholes, presumably due to the combined effect of suction above phreatic surface, simplified  
203 evaluation of effective stress state within the bank and partial drainage during cone penetration  
204 testing [39], the comparative analysis of field data allows identifying three main soil units. As  
205 shown in Figure 4 with respect to the cross-section No. 3, the stratigraphic arrangement includes:

- 206 • a 5 m thick, rather heterogeneous top layer of sands, silty sands and sandy silts (labelled as  
207 *Unit R*), forming the artificial river embankment;
- 208 • a predominantly silty unit (*Unit B*), 5 to 12 m thick, referable to the flood plain environment  
209 and corresponding to the upper part of the river embankment foundation subsoil;
- 210 • a clayey layer, detected at 12 to 30 m in depth from the bank crest, labelled as *Unit C*.

211 In this stratigraphic scheme, the groundwater table is located at approximately 6 m from the crest of  
212 the reshaped bank, at 30 m above mean sea level, i.e. close to the transition surface between *Unit R*  
213 and *Unit B*, as suggested by field data provided by the Casagrande-type piezometer installed into  
214 borehole BH-3 as well as by interpretation of CPTU pore pressure profiles. Such phreatic surface  
215 was found to be slightly sloping landwards, the hydraulic gradient  $i$  being equal to 4%. Similar  
216 stratigraphic arrangements and groundwater conditions were also identified from interpretation of  
217 site investigations located along alignments No. 1 and No. 2, although a certain horizontal spatial  
218 variability, in terms of both thickness and fine content of soil units *R* and *B* was observed. For this  
219 reason, the geotechnical model discussed in this study is specifically pertinent to section No. 3 (i.e.  
220 the closest alignment to the collapsed river embankment segment), whereas the geotechnical models  
221 of the other sections will not be presented because out of scope.

222 Accordingly, the geotechnical characterization of the different soil units relied on CPTU and  
223 SCPTU carried out in section No. 3, by applying semi-empirical correlations to field data. Results  
224 from laboratory tests were used as reference in order to validate the estimates of the mechanical  
225 parameters from in situ testing. The comparison between laboratory and field test results was  
226 mainly restricted to sediments forming the river embankment, since most of the samples were  
227 recovered in the upper 6 m. Furthermore, in view of the probabilistic analyses described in next  
228 sections, attention was primarily focused on the evaluation of the effective shear strength of the soil  
229 units. In particular, following previous successful experiences on natural silty mixtures referable to  
230 a very similar depositional environment of the Po river basin [40], the drained shear strength of *Unit*  
231 *R* and *Unit B*, expressed in terms of the effective friction angle at peak  $\varphi'$ , was determined using the  
232 well-established correlation proposed by Kulhawy and Mayne [41]. As regards the fine-grained  
233 *Unit C*, the estimates of  $\varphi'$  were instead obtained from an effective stress limit plasticity solution  
234 [42] whose effectiveness was proved on a large database of natural clays [43]. This approach is  
235 based on the assumption that the effective cohesion intercept  $c'$  is equal to 0, as reasonable in  
236 normally consolidated clays like those of *Unit C*.

237 Figure 3e shows estimates of  $\varphi'$  obtained from SCPTU7. The resulting profile exhibits an initial  
238 decreasing trend in the upper portion of *Unit R*, referable to a sort of thin “crust” typically detected  
239 by cone penetration or dilatometer tests in the topmost soil layers of the Po river basin  
240 embankments (e.g. [40,44]) and likely due to overconsolidation for desiccation-wetting cycles  
241 together with partial saturation effects. As a results, the values of  $\varphi'$  computed in this shallow thin  
242 lense were not considered as representative of *Unit R* and thus excluded from the statistical analysis  
243 presented herein.

244 Table 1 provides a summary of the statistical parameters computed for the effective shear strength  
245 of the different soil units, as obtained from the combined interpretation of SCPTU7, CPTU8 and  
246 CPTU9. The skewness of  $\varphi'$  was always set equal to zero, as a consequence of the virtually

247 symmetrical data distribution. It is worth observing that the range obtained for  $\phi'$  in *Unit R*  
 248 ( $32^\circ \pm 1.9^\circ$ ) is fully consistent with the values ( $31.1^\circ$ - $34^\circ$ ) provided by triaxial tests, whereas in *Unit*  
 249 *B* the effective friction angle from a few laboratory tests turned out to be close to the upper  
 250 boundary identified by the statistical moments of Table 1. Unfortunately, laboratory test results in  
 251 shearing were not available for *Unit C*, thus preventing any comparison between estimates of  $\phi'$ . It  
 252 is also interesting to notice that the values presented in Table 1 are consistent with those reported in  
 253 the study of Phoon and Kulhawy [45], which was based on an extensive literature review.  
 254 Finally, it must be mentioned that the uncertainties on  $\phi'$  shown above do not include the so-called  
 255 “transformation model” uncertainty, the attention being here primarily focused on the variability of  
 256 the mechanical (and hydraulic) parameters as a consequence of the inherent heterogeneity of the  
 257 investigated sediments. Nevertheless, it is worth emphasizing that, according to the recent study of  
 258 Ching et al. [46], the CPT- $\phi'$  transformation model [41] adopted in the present work for *Unit R* and  
 259 *Unit B* was found to be nearly unbiased and with a broad application range.

260

Soil type	Friction angle $\phi'$ (°)		
	mean value	standard deviation	skewness
<i>Unit_R</i>	32.0	1.90	0
<i>Unit_B</i>	28.8	3.20	0
<i>Unit_C</i>	24.9	2.40	0

271 Table 1 – Statistical parameters (mean, standard deviation and skewness) of the friction angle  $\phi'$ ,  
 272 for *Unit R*, *Unit B* and *Unit C*.

273

### 274 3.2 Unsaturated soil properties from evaporation tests

275 In order to characterize the soils forming the river embankment with respect to their hydraulic and  
 276 retention response, series of evaporation tests were performed on nine undisturbed samples  
 277 purposely collected near Section No. 3, at depths between 0.7 m and 1.7 m from the crest. Attention  
 278 was obviously focused on sediments of the river embankment top layer *Unit R*, where unsaturated

279 conditions are likely to apply. All tests were performed according to the procedure proposed by  
 280 Romano and Santini [47], which relies on a parameter optimization strategy for the determination of  
 281 unsaturated soil properties using evaporation data. In this study, the well-known and widely-used  
 282 hydraulic model proposed by van Genuchten [48] was adopted to fit the experimental data; thus,  
 283 hysteresis in the typical water retention behaviour of unsaturated soils was disregarded for the  
 284 prediction of the effective degree of saturation,  $S_e$ . Accordingly, this can be determined as follows:

$$285 \quad (11) \quad S_e(h) = \frac{\theta - \theta_r}{\theta_0 - \theta_r} = \left[ \frac{1}{1 + (\alpha_{VG} \cdot s)^{n_{VG}}} \right]^{m_{VG}}$$

286 where  $\theta$ ,  $\theta_0$  and  $\theta_r$  are the volumetric soil water content at the current stage, at saturation and in  
 287 residual conditions respectively,  $s$  is the soil suction, given by the difference between the pore air  
 288 pressure,  $u_a$ , and the pore water pressure,  $u_w$ , whilst  $\alpha_{VG}$  and  $n_{VG}$  are model parameters, mainly  
 289 influencing the inflection and the shape of the retention curve respectively. Some authors [49] also  
 290 refer to  $\alpha_{VG}$  as the inverse of suction value at which the soil starts to desaturate. It is useful to  
 291 remind that  $n_{VG}$  and  $m_{VG}$  are usually considered as inter-dependent parameters, defined as:

$$292 \quad (12) \quad m_{VG} = 1 - \frac{1}{n_{VG}}$$

293 In accordance with the Mualem's [50] model coupled with the parametrisation procedure suggested  
 294 by van Genuchten [48], the variation of soil permeability with suction was derived from the Soil  
 295 Water Retention Curve (SWRC), which describes the relationship between volumetric water  
 296 content and matric suction. Hence, the following equation was used:

$$297 \quad (13) \quad k_r = S_e^{0.5} \left[ 1 - \left( 1 - S_e^{1/m} \right)^m \right]^2$$

298 The above equation, typically referred to as Hydraulic Conductivity Function, defines the  
 299 relationship between the effective degree of saturation,  $S_e$ , and the relative permeability,  $k_r$ . The  
 300 hydraulic permeability of the soil is then obtained as the product of the saturated permeability,  $k_0$ ,  
 301 and the relative permeability,  $k_r$ .

302 Figure 5 shows the SWRCs obtained by fitting the available laboratory data using eq.(11). The plot  
 303 provides the effective degree of saturation  $S_e$  as a function of suction  $s$ . Although all the samples

304 were taken from the same soil unit, a significant degree of heterogeneity is observed on the  
305 hydraulic behaviour of the soil in partially saturated conditions.  
306 Based on such experimental results, a statistical interpretation of the hydraulic parameters of *Unit R*,  
307 expressed in terms of mean values, standard deviation, skewness and correlation structure, was  
308 carried out. It is worth observing that the amount of available laboratory test results can be  
309 considered as statistically significant for the proposed study, also considering that each evaporation  
310 test involved three independent measurements and that, at the same time, such dataset is  
311 significantly larger than those typically available in engineering practice. The computed mean  
312 values of the unsaturated hydraulic parameters of *Unit R*, together with standard deviation and  
313 skewness are listed in Table 2, whilst the relevant correlation matrix is provided in Table 3. The  
314 parameter  $m_{VG}$  was obviously excluded from the list of hydraulic input variables, being dependent  
315 on  $n_{VG}$ .

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### Hydraulic parameters of *Unit R*

	mean value	standard deviation	skewness
$\theta_r$ [m <sup>3</sup> /m <sup>3</sup> ]	0.079	0.078	0.542
$\theta_{sat}$ [m <sup>3</sup> /m <sup>3</sup> ]	0.395	0.041	0.026
$\alpha_{VG}$ [kPa <sup>-1</sup> ]	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 – Statistical moments (mean, standard deviation and skewness) of the unsaturated hydraulic parameters of soil *Unit R*.

	$\theta_r$ m <sup>3</sup> /m <sup>3</sup>	$\theta_{sat}$ m <sup>3</sup> /m <sup>3</sup>	$\alpha_{VG}$ kPa <sup>-1</sup>	$n_{VG}$ -	$\log(k_0)$ log(m/s)
$\theta_r$	1	0.0	0.0	0.37	-0.51
$\theta_{sat}$	-	1	0.34	0.69	0.63
$\alpha_{VG}$	-	-	1	-0.09	0.68
$n_{VG}$	-	-	-	1	0.23
$\log(k_0)$	-	-	-	-	1

Table 3 – Correlation matrix of the unsaturated hydraulic properties of soil *Unit R*.



339 It is worth mentioning that the statistical moments shown in Table 2 fall in the ranges typically  
340 reported in the literature. Indeed, according to a number of studies (e.g. [20,51-52]), based on either  
341 direct or indirect methods for the assessment of hydraulic parameters, typical ranges of the  
342 coefficient of variation ( $\text{CoV}_{(X)} = \sigma_X/\mu_X$ ) of the Van Genuchten – Mualem model parameters are:  
343  $\text{CoV}_{(\theta_r)} = 10\text{-}110\%$ ,  $\text{CoV}_{(\theta_{sat})} = 5\text{-}25\%$ ,  $\text{CoV}_{(\alpha_{VG})} = 20\text{-}100\%$ ,  $\text{CoV}_{(n_{VG})} = 3\text{-}20\%$ ,  $\text{CoV}_{(k_D)} = 100\text{-}$   
344  $300\%$ . Besides, the mean values of Table 2 turn out to be fully consistent with those reported by  
345 Santoso et al. [53]. Regarding *Unit B* and *Unit C*, only the permeability at saturation,  $k_0$ , was taken  
346 into account, since both units are permanently below the phreatic line. Mean values of the  
347 permeability, as obtained from the application of empirical correlations to piezocone data [54], turn  
348 out to be  $1.88 \cdot 10^{-6}$  m/s and  $1.30 \cdot 10^{-9}$  m/s for *Unit B* and *Unit C*, respectively. It must be emphasized  
349 that the permeability of both units was considered as a deterministic parameter in the probabilistic  
350 analyses proposed herein.

351

#### 352 **4. Development of the seepage model for the stability analyses in** 353 **transient conditions**

354 The seepage and stability analyses were carried out with reference to a 2D river embankment model  
355 based on the geometry, stratigraphic conditions, geotechnical and hydrological data of section No. 3  
356 of the river Secchia (Figure 4), as it used to be prior to failure, i.e. 7 m high, with the outer and  
357 inner slope angles equal to  $30^\circ$  and  $33^\circ$  respectively. In order to properly assess the stability of an  
358 existing river embankment with respect to a specific flooding event, it is necessary to undertake  
359 transient seepage analyses, accounting for both river level fluctuations and rainfall infiltration,  
360 starting from realistic initial conditions. Accordingly, the soil forming the river embankment,  
361 namely soil *Unit R* in this study, must be assumed as partially saturated, with relevant implications  
362 on both the seepage process and soil shear strength that will be discussed later. In particular, in the  
363 absence of specific measurements for the studied river embankment segment, a suitable initial  
364 suction distribution into the bank, which might be considered as typical during a period of

365 significant rainfall events, was firstly sought. Following previous experiences of other Authors (e.g.  
366 [1,55-58]), the distribution eventually adopted assumes that suction is maximum in the river  
367 embankment core and approximately equal to zero at the free surface.

368 As a result, taking the water table at 30 m above the means sea level (m.s.l.), close to the transition  
369 surface between *Unit R* and *Unit B* (see Fig. 4), suction was assumed to linearly increase up to 39  
370 kPa in correspondence of the centre of the bank, at 4 meters above the phreatic line, and then to  
371 decrease to zero close to the bank crest.

372 Flow through an earthen structure highly depends on the relative permeability of the fill material,  
373 which in turn depends on its degree of saturation. The transient unsaturated-saturated flow was  
374 modelled using the 2D Finite Element code SEEP/W [59], assuming the effective degree of  
375 saturation and the relevant hydraulic permeability derived from the application of the van  
376 Genuchten-Mualem model [48], as discussed in §3.2. The FE numerical solution is based on the  
377 Generalized Darcy Law for transient seepage conditions, given by:

$$378 \quad (14) \quad \mathbf{q} = \frac{\partial \theta}{\partial t} - k_r k_0 \nabla \left( \frac{u_w}{\gamma_w} + z \right)$$

379 where  $z$  is the vertical elevation and  $\mathbf{q}$  is the boundary flux per unit area. When the water storage in  
380 the model does not vary with time, steady-state conditions apply, basically corresponding to  
381 significantly high persistency of the hydrometric peak.

382 Positive and negative pore water pressure distributions obtained at the end of the seepage analysis  
383 were then imported into the code SLOPE/W [60] and assumed as input data for the riverbank  
384 stability calculations, using limit equilibrium methods. Among the different available approaches,  
385 the Morgenstern and Price [61] method was eventually selected to perform the stability analyses in  
386 transient flow conditions.

387 Slip surfaces were generated randomly, according to suitable pre-defined geometrical constraints,  
388 consisting in the ranges for the entry zone and the exit zone of the sliding mechanism on the ground  
389 surface, together with the so-called “minimum depth” (corresponding to the minimum height of

390 LEM slices). In this way, a significant collapse mechanism could be identified, while excluding  
391 potential local shallow slip surfaces (see Fig. 6). The minimum slip surface depth was assumed to  
392 be 1.5 m and 3.8 m for the inner and outer instability mechanisms, respectively. Furthermore, the  
393 potential slip surfaces were all circular, as actually observed in the collapse occurred in January  
394 2014.

395 Regarding soil shear strength, the limit equilibrium analyses performed in this study made use of  
396 the Vanapalli et al. [62] failure criterion, which is implemented in SLOPE/W. As many other  
397 strength criteria for unsaturated soils, this approach derives from the linear shear strength equation  
398 originally proposed by Fredlund et al. [63], extending such formulation to account for the impact of  
399 non-linearity of the soil water retention curve on the resulting shear strength relationship. As a  
400 result, the shear strength of an unsaturated soil is assumed to vary with the degree of saturation ( $S_e$ )  
401 and the matric suction ( $u_a - u_w$ ), according to the following expression:

$$402 \quad (15) \quad \tau = c' + (\sigma_n - u_a) \tan \varphi' + (u_a - u_w) S_e \tan \varphi'$$

403 with  $\sigma_n$  = the total normal stress,  $c'$  = effective cohesion,  $\varphi'$  = effective stress friction angle.

404 The first part of the equation describes the saturated shear strength, which is a function only of the  
405 normal stress since the shear strength parameters  $c'$  and  $\varphi'$  are assumed as constant for a saturated  
406 soil. The second part [i.e.,  $(u_a - u_w) \cdot S_e \cdot \tan \varphi'$ ] provides the shear strength contribution due to suction,  
407 which can be predicted using the soil water retention curve [64]. In particular, the formulation  
408 described by eq.(15) fulfils a number of well-known experimental evidences reported by various  
409 Authors (e.g. [62,65]): when the soil begins to desaturate, the unsaturated soil strength contribution  
410 varies according to a non-linear function of suction, as long as the matric suction remains above the  
411 air entry value (AEV), this latter corresponding to the point at which air enters the largest pores of  
412 the soil [50]. By contrast, when suction is below AEV, the unsaturated shear strength is equal to  $(u_a$   
413  $- u_w) \cdot \tan \varphi'$ . In saturated conditions, when the pore-air pressure,  $u_a$ , is equal to the pore-water  
414 pressure,  $u_w$ , eq. (15) turns into the classical Mohr – Coulomb failure criterion.

415 With respect to the shear strength values adopted in the analyses, a few points must be emphasized.  
416 First of all, it is worth remarking that the use of data only from the evaporation tests prevented from  
417 dealing with soil hysteresis in the water retention behaviour. As a matter of fact, the seepage  
418 process to be modelled in this study is not truly referable to wetting paths, but rather to scanning  
419 paths, which in turn would require specific laboratory tests for characterization. On the other hand,  
420 a few preliminary analyses based on the parameters estimated for the wetting branch, according to  
421 suggestions of Likos et al. [52], showed that the use of data from a main drying curve generally  
422 does not provide results on the unsafe side in terms of reliability assessment, which is indeed the  
423 main focus of this study. This outcome is due to a combination of different governing factors that  
424 result in opposite effects on the numerical assessment of the riverbank stability and the prevalence  
425 of one effect on the others should be analysed in each specific case. Indeed, although the  
426 assumption of non-hysteretic hydraulic behaviour might tend to overestimate the suction values for  
427 an assigned effective degree of saturation, the relative permeability would be then underestimated  
428 by the van Genuchten model, with evident consequences on the flow regime and leading, at the end  
429 of high water events, to a minor impact on the phreatic line, particularly when initial conditions are  
430 defined in terms of suction.

431

## 432 **5. Probabilistic stability analysis**

433 The probabilistic analysis of the riverbank stability was organized into two main stages, referred to  
434 as “First-level probabilistic analysis” and “Second-level probabilistic analysis” respectively. The  
435 first includes a few preliminary analyses based on the assumption that the soil friction angle  $\phi'$  is  
436 the only random variable. Both steady-state seepage conditions, typically suggested by guidelines,  
437 and transient seepage in partially saturated soils, were modelled. Indeed, although the steady-state  
438 seepage turns out to be the most critical situation for the stability of a river embankment, only a  
439 transient seepage approach, accounting for fluctuations of the river water level and rainfall

440 infiltration, can realistically identify the actual margins of safety of the structure during a specific  
441 flooding event. Obviously, the variability of the friction angle has no effects on the finite element  
442 seepage analysis, thus only affecting slope stability results.

443 By contrast, in the “Second-level probabilistic analysis”, the riverbank reliability analysis was  
444 carried out solely under transient seepage conditions, accounting for uncertainties in both the  
445 effective friction angle and the unsaturated soil hydraulic parameters. In this way, the different  
446 impact produced by different sources of uncertainties in soil parameters may be identified.

447 At this point, it must be observed that a comprehensive stochastic analysis of the seepage through  
448 the river embankment should also consider the aleatory uncertainty associated with the initial pore  
449 water pressure distribution [66], which in turn depends on the river water level fluctuations. In this  
450 study, however, such aspect was disregarded, being the attention basically focused on the variability  
451 of geotechnical parameters and its effects on the riverbank reliability.

452

## 453 **5.1 First-level probabilistic analysis**

### 454 **5.1.1 Steady state conditions**

455 The steady state seepage analysis was performed assuming the river level at the maximum  
456 hydrometric height recorded during the January 2014 flooding event, i.e. at 35.9 m above mean sea  
457 level [21], whilst the water table on landward side was located at the ground level. Constant values  
458 of the hydraulic conductivities were adopted for the different soil units, namely equal to the  
459 saturated permeability  $k_0$  reported in Table 2 for *Unit R* and to the values of  $k_0$  mentioned in § 3.2  
460 for *Unit B* and *Unit C*. Figure 7 shows the computed pore water pressure (PWP) and the  
461 corresponding pressure head distributions, used in turn as input for the limit equilibrium analyses.  
462 The latter are based on the assumption that the soil shear strength obeys the effective stress Mohr-  
463 Coulomb failure criterion and that the friction angle of the river embankment soil unit (*Unit R*)  
464 follows a normal distribution, described by the statistical moments reported in Table 1 (mean shear

465 strength =  $32.0^\circ$ , standard deviation =  $1.9^\circ$ ). In these analyses, the contribution to shear strength due  
466 to suction is disregarded. The shear strength parameters of the underlying soil units, i.e. *Unit B* and  
467 *Unit C*, were considered as deterministic variables, the main goal being to investigate the effect of  
468 soil strength variability only within the river embankment. In this case, the model uncertainty is  
469 described by just one random variable and therefore the application of the *Point Estimate Method*  
470 requires only two combinations. For each point estimate combination, the most critical slip surface,  
471 in terms of safety factor, was randomly searched.

472 As mentioned in §2, these preliminary analyses were performed using both PEM and MCM, in  
473 order to assess the accuracy of the probability of failure provided by the *Point Estimate Method*  
474 compared to results of the robust *Monte Carlo* approach, the latter requiring a relatively moderate  
475 computational effort when uncertainty in soil parameters is limited to a single random variable.  
476 Values of the safety factor and probability of failure obtained from the probabilistic analyses are  
477 summarized in Table 4. A substantial agreement between the MCM and PEM results can be  
478 observed in this case, thus providing support for the application of only the *Point Estimate Method*  
479 to the whole stability problem discussed in this paper. Agreement between the two probabilistic  
480 methods was also documented by Vannucchi [67] with respect to other geotechnical applications.  
481

Probabilistic Analysis Results – Steady state seepage conditions – PEM and MCM

Safety Factor	Outer slope		Inner slope	
	PEM	MCM	PEM	MCM
Mean ( $\mu_{SF}$ )	1.013	1.013	1.405	1.405
Standard deviation ( $\sigma_{SF}$ )	0.046	0.047	0.106	0.107
Reliability index ( $\beta_{SF}$ )	0.283	0.274	3.821	3.791
Probability of failure (%)	38.9	39.9	$6.7 \cdot 10^{-3}$	$7.3 \cdot 10^{-3}$

482 Table 4 – Probabilistic results of limit equilibrium analyses in steady state condition, for outer and  
483 inner slopes, with deterministic soil bank hydraulic parameters.

484

485 It is worth observing that the stability analyses in steady seepage conditions, though not  
486 representative for the specific flooding event, provide a sort of reference benchmark and useful  
487 information with regard to the existing margin of safety of the river embankment. Indeed, according  
488 to the computed values of the reliability index  $\beta_{SF}$ , which turn out to be very low, the stability of the  
489 outer slope in case of persistent high river water levels appears critical. By contrast, a high  
490 reliability index value (thus implying a low probability of failure) was obtained for the most critical  
491 surface of the inner slope.

492

### 493 ***5.1.2 Transient seepage conditions***

494 In transient seepage analyses, the river water level fluctuation was modelled as time-dependent  
495 boundary condition on the riverside FE mesh nodes, expressed in term of total hydraulic head.  
496 Rainfall infiltration was simulated as water flux through the boundary surface, based on the  
497 hydrometric values and precipitation data recorded in close proximity to the investigated breached  
498 area, from 25 December 2013 to the flooding event date (19 January 2014). The daily river levels  
499 and rainfall recorded by the competent Regional Authority are plotted in Figure 8, together with the  
500 approximated profile of the total hydraulic head variation versus time, applied at the riverside  
501 boundary of the numerical model. Figure 9 shows the computed pore water pressure distributions at  
502 the initial and final stage of transient seepage analysis. As regards the unsaturated hydraulic  
503 parameters of *Unit R*, here treated as deterministic variables, the mean values of Table 2 were  
504 adopted.

505 The subsequent probabilistic limit equilibrium analysis, based on the PEM approach, resulted in  
506 very high values of the reliability index  $\beta_{SF}$  (i.e. very low probabilities of failure), especially for the  
507 inner slope (Table 5). Since the probability of failure provided by PEM may suffer from a lack of  
508 accuracy at very small probability levels, in this study a threshold value equal to  $10^{-3}\%$  was  
509 assumed as reference for the minimum value of  $P_f$ , hence the reason for  $P_f$  expressed as  $<10^{-3}\%$  in

510 Table 5. On the other hand, probabilities of failure lower than  $10^{-3}\%$  does not seem to provide  
 511 additional information with respect to the riverbank stability conditions.

512

Probabilistic Analysis Results – Transient seepage conditions

Safety Factor	Outer slope	Inner slope
Mean ( $\mu_{SF}$ )	1.346	2.077
Standard deviation ( $\sigma_{SF}$ )	0.063	0.156
Reliability index ( $\beta_{SF}$ )	5.492	6.904
Probability of failure ( $P_f, \%$ )	$< 10^{-3}$	$< 10^{-3}$

513 Table 5 – Probabilistic results of M-P limit equilibrium analyses in transient seepage condition, for  
 514 outer and inner slopes, with deterministic soil bank hydraulic parameters.

515

## 516 **5.2 Second-level probabilistic analysis**

517 The second-level probabilistic analysis was performed in order to investigate the effect of multiple  
 518 sources of uncertainties in soil parameters (i.e. both shear strength and unsaturated hydraulic  
 519 properties) on the assessment of riverbank stability, expressed in terms of the degree of uncertainty  
 520 associated with the safety factor.

521 For this purpose, three different sets of probabilistic analyses were devised, according to the  
 522 different assumptions adopted in the cases specified below:

523 *Case 1:* friction angle ( $\varphi'$ ) of *Unit R* assumed as random variable and hydraulic parameters ( $\vartheta_r, \vartheta_0,$   
 524  $\alpha_{VG}, n_{VG}, k_0$ ) as deterministic variables, equal to their mean values.

525 *Case 2:* shear strength angle ( $\varphi'$ ) and hydraulic parameters ( $\vartheta_r, \vartheta_0, \alpha_{VG}, n_{VG}, k_0$ ) of *Unit R* assumed  
 526 as non-correlated random variables.

527 *Case 3:* shear strength angle ( $\varphi'$ ) and hydraulic parameters ( $\vartheta_r, \vartheta_0, \alpha_{VG}, n_{VG}, k_0$ ) of *Unit R* assumed  
 528 as correlated random variables.

529 As a matter of fact, *Case 1* corresponds to the first-level probabilistic analysis in transient seepage  
 530 condition commented in § 5.1.2.



531 The remaining two cases were analysed following the methodological approach already described,  
532 i.e. transient seepage analyses were carried out using appropriate hydraulic soil parameters and  
533 then, based on the computed pore water pressure distributions, for each point estimate combination  
534 the most critical slip surface was randomly searched. Hence, such analyses are not based on a  
535 deterministic choice of a predefined critical failure surface, which therefore may vary as different  
536 point estimate combinations are adopted. In both *Case 2* and *Case 3*, probabilistic analyses  
537 considered a total of 6 random variables: the friction angle  $\varphi'$  and 5 hydraulic parameters ( $\theta_r$ ,  $\theta_{sat}$ ,  
538  $\alpha_{VG}$ ,  $n_{VG}$ ,  $k_0$ ) of *Unit R*. In this way, the application of PEM resulted in 64 combinations of point  
539 estimate locations. Histograms of each random variable, together with the indication of the point  
540 estimate locations ( $X_+$  and  $X_-$ ) and the associated weights ( $P_+$  and  $P_-$ ), are shown in Figure 10.  
541 The method consists in calculating the safety factor  $SF$  for each set of parameters in a deterministic  
542 way. According to the procedure described in § 2.1, results were then suitably processed in order to  
543 obtain the mean  $\mu_{SF}$  and the standard deviation  $\sigma_{SF}$  of safety factor  $SF$ , assumed as a normally  
544 distributed random variable.

545

## 546 **6. Discussion of results**

547 Results of the probabilistic analyses for the three cases investigated in the second-level probabilistic  
548 analysis are summarized in Figures 11 and 12, plotted in terms of probability density function  
549 (PDF) of the safety factor, cumulative density function (CDF) and probability of failure ( $P_f$ )  
550 associated with the safety factor, for both the outer and the inner riverbank slopes. It is worth  
551 mentioning here that the probability of failure can be easily determined from the cumulative density  
552 function for a safety factor equal to 1 ( $CDF_{SF=1}$ ), since  $P_f(\%) = 100 \times CDF_{SF=1}$ .

553 Figure 11 clearly shows that the mean value of the safety factor is approximately equal to 1.3 for  
554 the outer slope and close to 2.0 for the inner slope, with minor differences among the three cases  
555 mentioned above. Hence, the riverside zone appears to be significantly more stable than the

556 landward zone. In general, it is immediate to observe that for this case study standard safety factors  
557 are sufficiently high; in fact, with regards to the most probable causes of the sudden collapse  
558 occurred in January 2014, other possible local structural weaknesses – like the extensive presence  
559 of animal burrows – were eventually advocated having triggered the catastrophic event [21].  
560 However, this probabilistic study allows identifying very significant differences in the evaluation of  
561 the riverbank reliability, as a consequence of the different assumptions adopted in the three series of  
562 numerical analyses, which deserve particular attention in the light of common risk assessment  
563 procedures. In *Case 2* and *Case 3*, both accounting for the variability of hydraulic parameters in  
564 addition to shear strength, the uncertainty degree in the estimate of the safety factor increases  
565 considerably, with associated rather low values of the reliability index  $\beta$ , always lower than 3.5.  
566 Accordingly, the probability of failure turns out to be non-negligible, namely higher than  $10^{-2}\%$  for  
567 both the inner and outer slope, whilst extremely low values of  $P_f (< 10^{-3} \%)$  were obtained when the  
568 only source of uncertainty was assumed to lie in shear strength (*Case 1*).

569 In particular, the probability density functions plotted in Figure 11 provide clear evidence of an  
570 increase in the standard deviation of the safety factor when the stability analyses are carried out  
571 under stochastic unsaturated transient seepage conditions. The effect may be appreciated in both  
572 riverbank slopes, although it is undoubtedly more noticeable for the riverside stability analyses,  
573 being the shape of the probability distributions associated with *Case 2* and *Case 3* significantly  
574 wider than the “thin” shape of *Case 1*.

575 Besides, the probability of failure provided by the numerical analyses of *Case 3*, reflecting the  
576 uncertainties of the unsaturated hydraulic parameters as well as their correlation structure, is one  
577 order of magnitude smaller than that obtained in *Case 2*, the latter being based on the assumption of  
578 no correlation between the parameters. Such outcome is consistent with results reported by Zhang et  
579 al. [68-69] with respect to slope stability problems. Indeed, additional information on the input  
580 parameters result in a better knowledge of them, thus leading to a reduction of the degree of  
581 uncertainty. This point was extensively discussed also by Phoon et al. [20], who observed that

582 correlations between unsaturated hydraulic parameters should be investigated as a preliminary step  
 583 in any probabilistic study instead of assuming a priori their independence for expediency.

584 Furthermore, Figure 13 shows results of a sensitivity analysis on the input parameters, i.e. shear  
 585 strength and hydraulic parameters, aimed at investigating their relative importance on the river  
 586 embankment response. Such relative contribution was quantified in terms of the variance of the  
 587 safety factor,  $\sigma_{SF}^2$ , defined according to eq.(8). In particular, the contribution of the hydraulic  
 588 parameters to  $\sigma_{SF}^2$  was simply evaluated as the difference between the safety factor variance  
 589 computed in *Case 2* ( $\sigma_{SF,c2}^2$ ) or, alternatively, in *Case 3* ( $\sigma_{SF,c3}^2$ ) and the safety factor variance  
 590 associated with *Case 1* ( $\sigma_{SF,c1}^2$ ), the latter being based on the uncertainty in shear strength ( $\phi'$ ) only.

591 Accordingly, for *Case 2* and *Case 3*, the per cent relative contribution of the effective friction angle  
 592 ( $\sigma_{\%,\phi'}^2$ ) and the hydraulic parameters ( $\sigma_{\%,hp}^2$ ) to the safety factor variance can be evaluated as  
 593 follows:

$$594 \quad (16a) \quad \sigma_{\%,\phi'}^2 = 100 \cdot \sigma_{SF,c1}^2 / \sigma_{SF,c2}^2 \quad \text{Case 2}$$

595 or

$$596 \quad (16b) \quad \sigma_{\%,\phi'}^2 = 100 \cdot \sigma_{SF,c1}^2 / \sigma_{SF,c3}^2 \quad \text{Case 3}$$

$$597 \quad (17a) \quad \sigma_{\%,hp}^2 = 100 \cdot (\sigma_{SF,c2}^2 - \sigma_{SF,c1}^2) / \sigma_{SF,c2}^2 \quad \text{Case 2}$$

598 or

$$599 \quad (17b) \quad \sigma_{\%,hp}^2 = 100 \cdot (\sigma_{SF,c3}^2 - \sigma_{SF,c1}^2) / \sigma_{SF,c3}^2 \quad \text{Case 3}$$

600 According to results plotted in Figure 13, the unsaturated hydraulic parameters appear to have the  
 601 largest influence on the uncertainty of the safety factor, with percentages of contribution in the  
 602 ranges 72-84% and 79-83% for the outer slope and inner slope respectively.

603 A final parametric study was undertaken in order to gain a better insight into the effect of the  
 604 coefficient of variation of the only friction angle  $\phi'$ ,  $CoV_{(\phi')}$ , on the probability of failure, with  
 605 respect to both riverbank slopes. For this purpose, three different values of  $CoV_{(\phi')}$ , selected within

606 the typical interval (i.e. 5-15%) quoted for this statistical parameter by various authors (e.g.  
607 [3,45,70,71]), were investigated, while assuming the unsaturated hydraulic properties either as  
608 deterministic or correlated random variables. Results of these series of analyses, expressed in terms  
609 of probability of failure versus  $\text{CoV}_{(\varphi)}$ , are plotted in Figure 14. For  $\text{CoV}_{(\varphi)} = 6\%$ , corresponding to  
610 the value computed from the available experimental estimates, the values of  $P_f$  coincide with those  
611 previously calculated in *Case 1* (i.e. deterministic transient seepage) and *Case 3* (i.e. stochastic  
612 transient seepage based on correlated hydraulic random variables).

613 As the coefficient of variation of the shear strength increases from 6% to 15%, the impact of  $\varphi'$  on  
614 the variance of the safety factor was found to consistently increase, causing in turn a decrease in the  
615 relative importance of the hydraulic parameters on the output. However, Figure 14 clearly shows  
616 that the difference between the probability of failure obtained under the opposite hypotheses of  
617 stochastic and deterministic transient seepage remains significant as long as  $\text{CoV}_{(\varphi)}$  does not exceed  
618 10% for the outer riverbank slope and 15% for the inner slope.

619 This outcome demonstrates that for usual values of uncertainty degree of the effective friction  
620 angle, the variability of the unsaturated soil hydraulic parameters plays a crucial role in the  
621 assessment of the probability of failure of the riverbank slopes. Hence, neglecting the intrinsic  
622 variability of such parameters, even in soils assumed as relatively homogenous from a geotechnical  
623 point of view, may lead to estimates of the probability of failure which are not consistent with the  
624 real risk and typically non conservative. Further investigations and additional datasets from specific  
625 case studies are obviously required in order to confirm the above results and draw more  
626 comprehensive conclusions.

627

## 628 **7. Conclusions**

629 This paper has presented a probabilistic study aimed at exploring the role of partial saturation of  
630 soils and of intrinsic variability of the relevant hydraulic parameters, beside shear strength, on the

631 stability of existing river embankments. The issue has been discussed with reference to actual data  
632 of a specific 20m-long stretch of the river Secchia banks (northern Italy), which was extensively  
633 investigated following its catastrophic sudden collapse occurred in January 2014, after a period of  
634 intense rainfall. The large and varied geotechnical database related to this case study has enabled  
635 the development of a detailed geotechnical model of the breached segment, inclusive of the  
636 mechanical and hydraulic behaviour of the sediments forming the unsaturated river embankment,  
637 thus allowing sound probabilistic analyses supported by experimental results.

638 Uncertainties on geotechnical data are typically disregarded in standard practice and only a very  
639 limited number of research contributions have considered the effect of the variability of hydraulic  
640 soil properties on riverbank stability. Furthermore, according to recommendations of current  
641 geotechnical codes and standards, the assessment of riverbank stability is generally based on the  
642 over-simplified assumption of steady state seepage in equilibrium with the highest possible river  
643 level.

644 In this study, three key features have been taken into consideration: 1) the time-dependent hydraulic  
645 boundary conditions due to water level fluctuations in the river, thus requiring a transient seepage  
646 analysis; 2) the unsaturated initial state of the river embankment; 3) the uncertainty in the  
647 geotechnical parameters, including those describing the unsaturated behaviour of sediments.

648 The probabilistic analyses have been carried out using the Point Estimate Method, a widely  
649 recognized procedure for slope reliability analyses, which appears to offer significant advantages in  
650 terms of efficiency over the more robust Monte Carlo method where the assessment of the  
651 probability of failure can be computationally intensive.

652 The reason for adopting this simplified uncertainty propagation method is twofold. Infact, apart  
653 from its efficiency and rather straightforward implementation procedure, which make the approach  
654 attractive for use also in routine risk analyses, the idea behind the study is basically to explore the  
655 relative weight of a number of random variables on the stability assessment of a river embankment,  
656 expressed in terms of probability of failure.

657 Although the actual safety factors of both inner and outer slopes of the Secchia river embankment  
658 are generally far from unity, thus suggesting that the January 2014 failure should be most likely  
659 seen as due to lack of local integrity for animal burrows, the results presented in this paper have  
660 proved that the probability of failure is strongly influenced by the suction distribution, which in turn  
661 depends on the hydraulic parameters adopted in the analyses. When uncertainty in unsaturated  
662 hydraulic parameters is taken into account, the probability of failure turns out to be significantly  
663 higher than that obtained on the assumption that shear strength is the only random variable, the  
664 difference being in this case of various orders of magnitude. This study has also shown that for the  
665 usual uncertainty degree of shear strength, the variability of the unsaturated soil hydraulic  
666 parameters has a major impact on the resulting probability of failure, for both riverbank slopes.  
667 Hence, not only the unsaturated transient seepage conditions are of outmost importance in the  
668 assessment of riverbank stability, but also underestimating the effect of the intrinsic variability of  
669 hydraulic parameters, even in soils assumed as relatively homogenous, may lead to probabilities of  
670 failure which are not consistent with the actual risk and potentially non-conservative. The latter  
671 aspect, which is typically neglected in routine risk assessment procedures either for lack of relevant  
672 experimental data or lack of awareness of the potential consequences, should be taken in careful  
673 consideration instead.

674 Further investigations and additional datasets from specific case studies would be required in order  
675 to confirm the results discussed in this study and draw more comprehensive conclusions. It is  
676 finally worth observing that, in spite of a certain roughness, the Point Estimate Method has proved  
677 to clearly capture the effect of the intrinsic variability of the unsaturated soil hydraulic properties on  
678 the reliability analysis of the river embankment.

679

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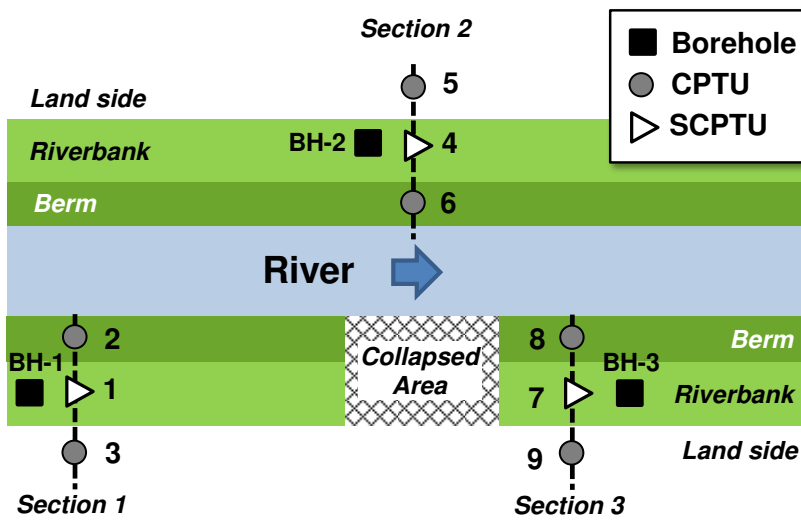
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**Figure 1** – Images of the breached area during the River Secchia flooding in January 2014.



**Figure 2** - Sketch of the investigated area with location of piezocone tests and boreholes.

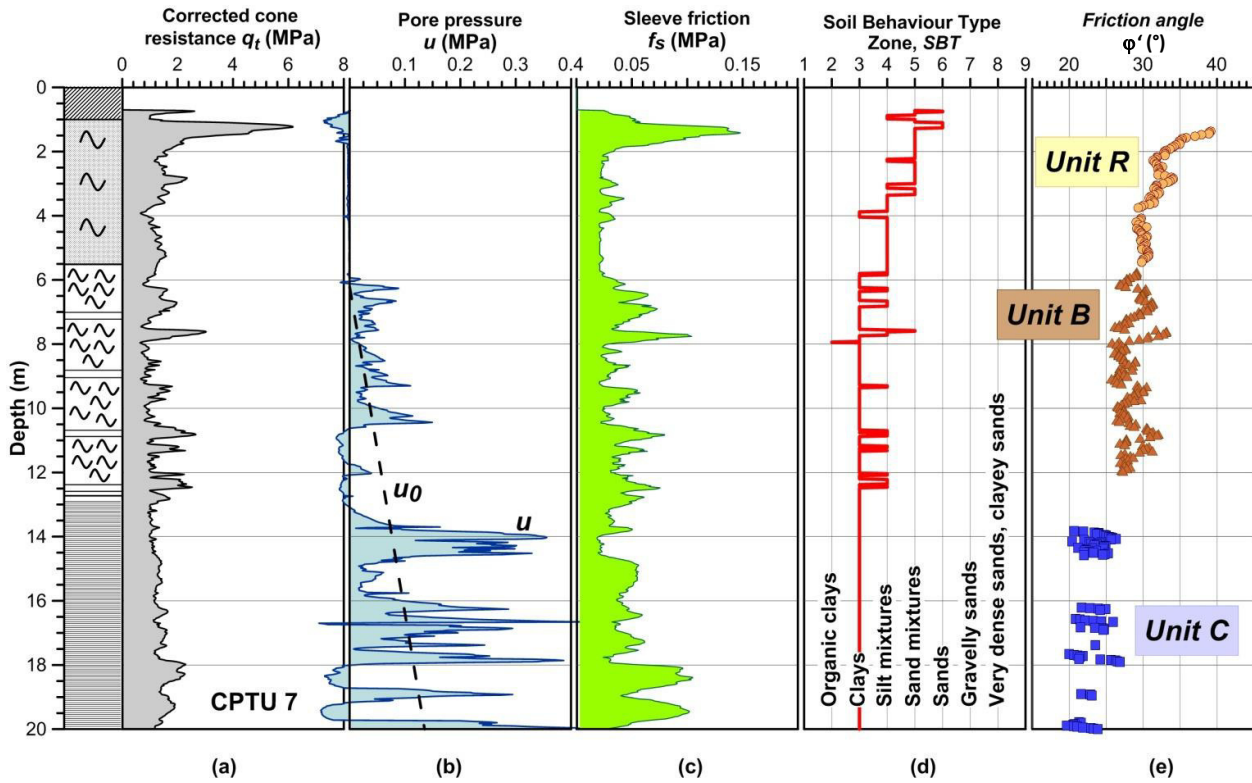


Figure 3 - SCPTU 7 log profiles and CPTU-based soil classification.

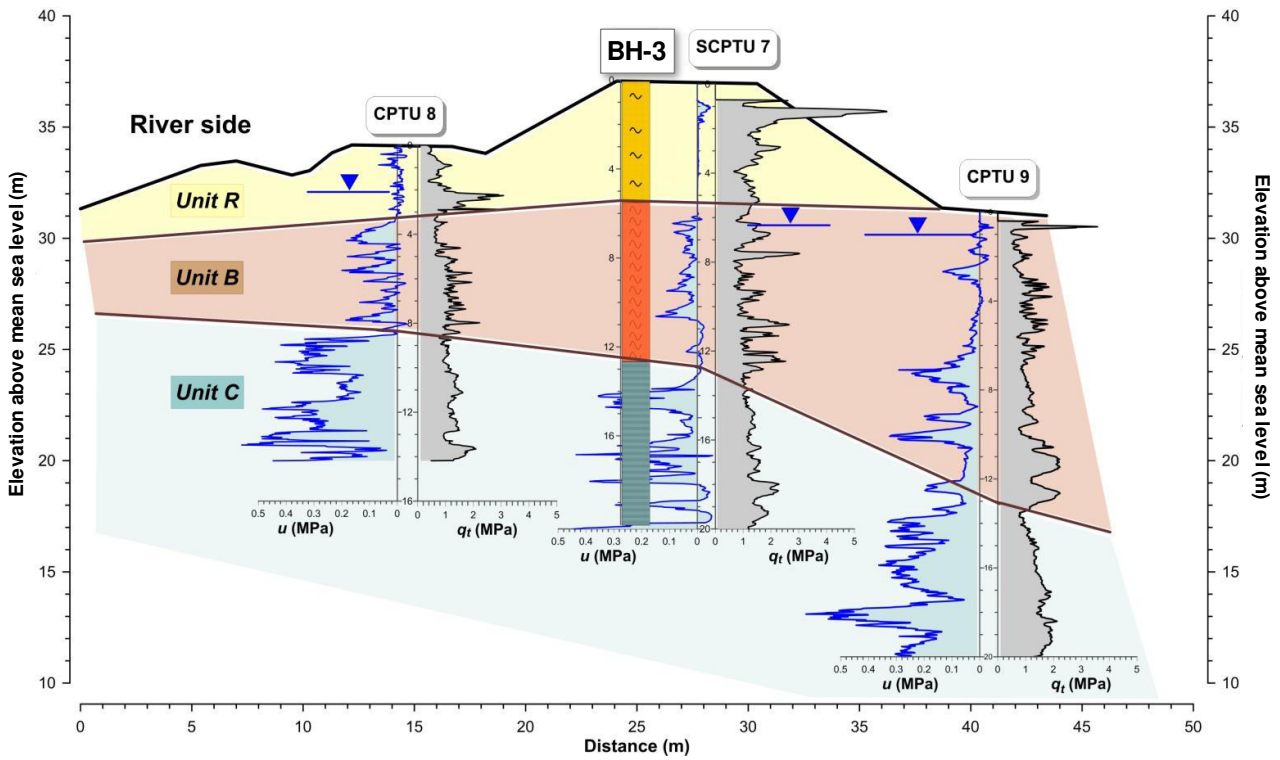
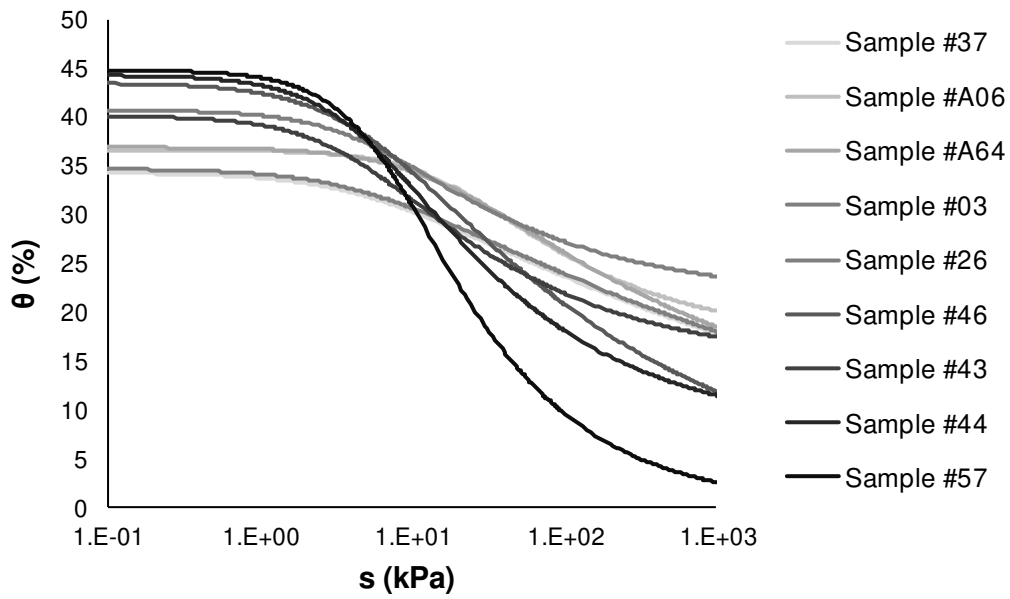
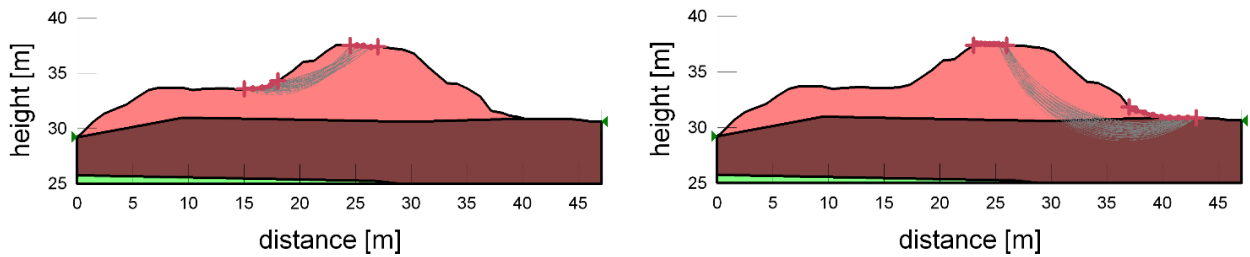


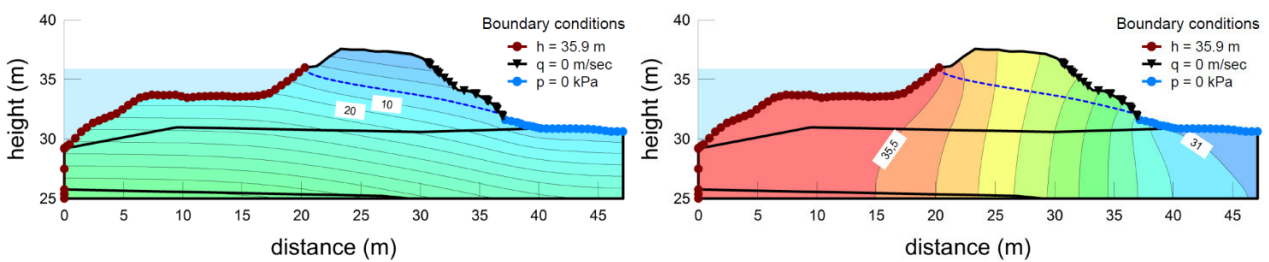
Figure 4 - Stratigraphic model along cross-section No. 3.



**Figure 5** – Soil water retention curves determined from laboratory experiments.

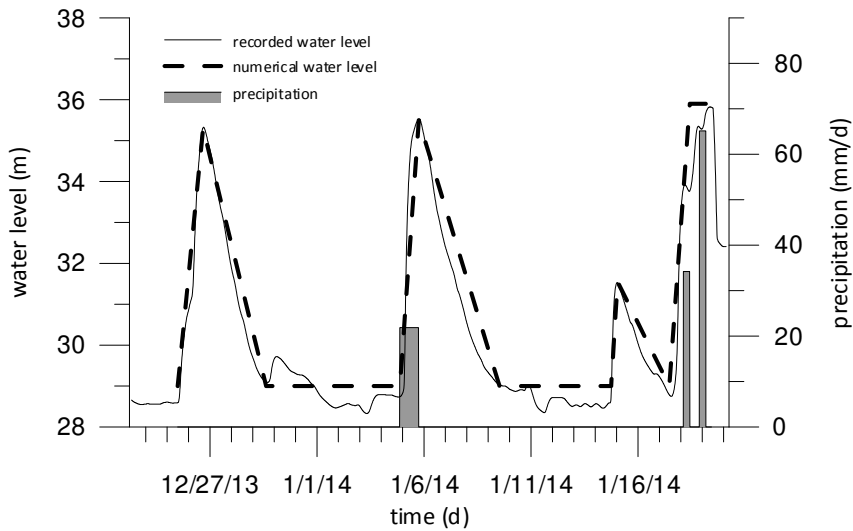


**Figure 6** – Typical slip surfaces investigated in stability analyses for inner (left) and outer (right) slopes.

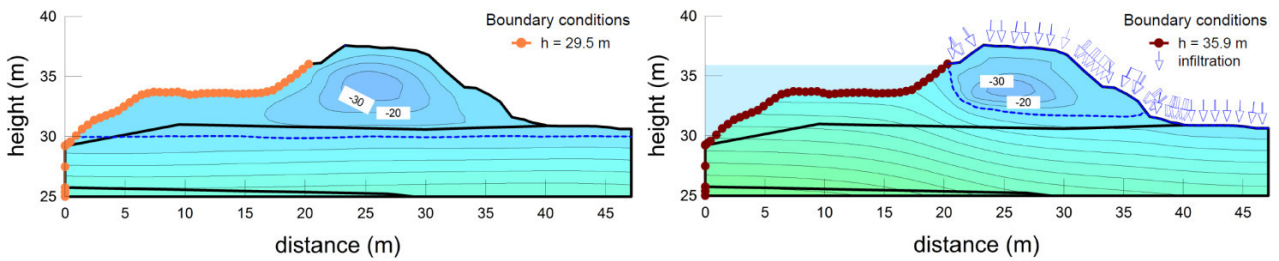


**Figure 7** – Results of the steady state seepage analysis: (left) pore water pressure distribution (isoline increment = 10 kPa) and (right) total head distribution (isoline interval = 0.5 m).





**Figure 8** – Flood hydrograph, rainfall hyetograph and numerical total hydraulic head boundary condition recorded and modelled from 25 December 2013 to 19 January 2014.



**Figure 9** – Pore water pressure distribution in the initial (left) and final (right) stage of transient seepage analysis (the increment between two adjacent isolines is 10 kPa).

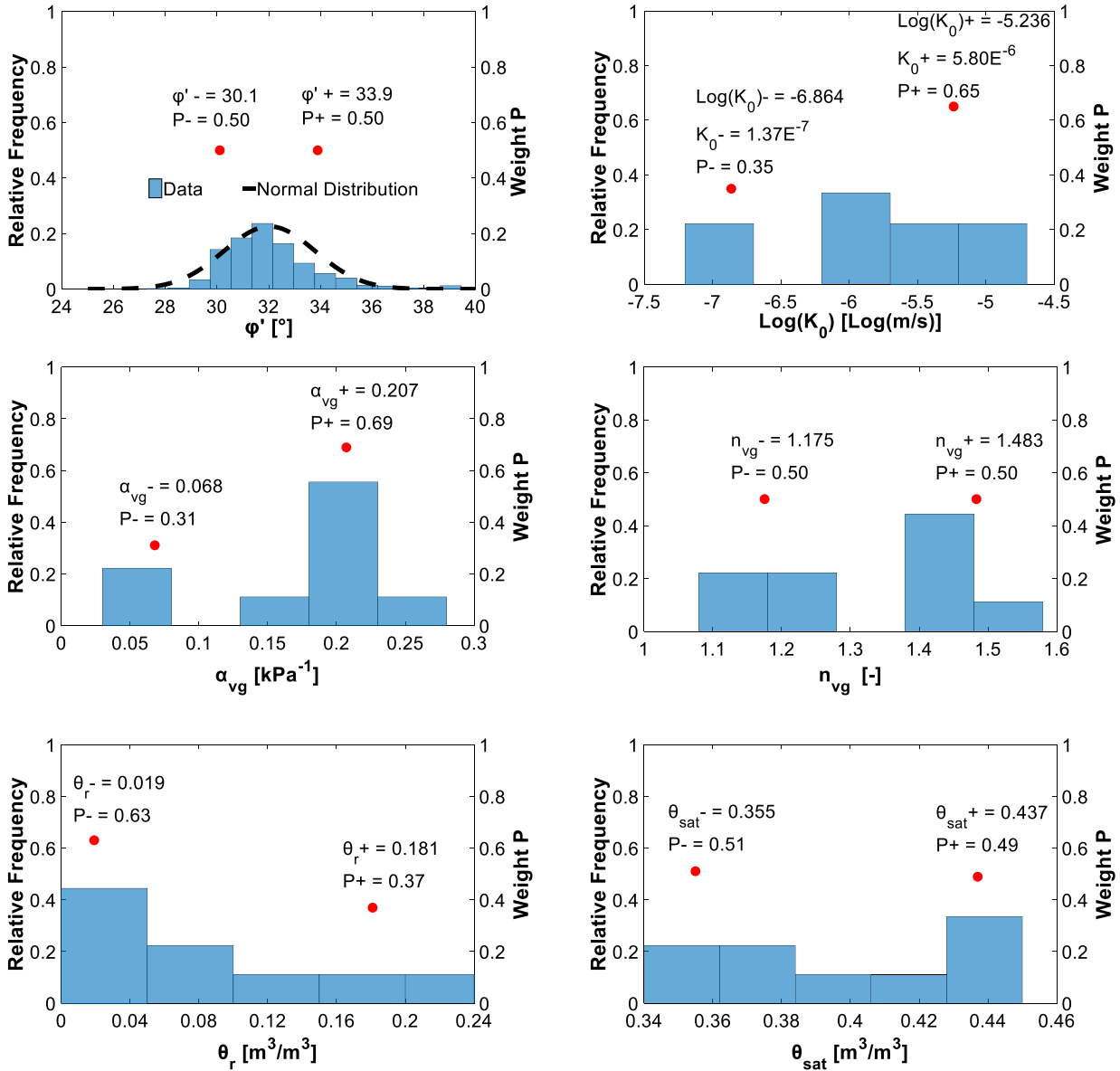
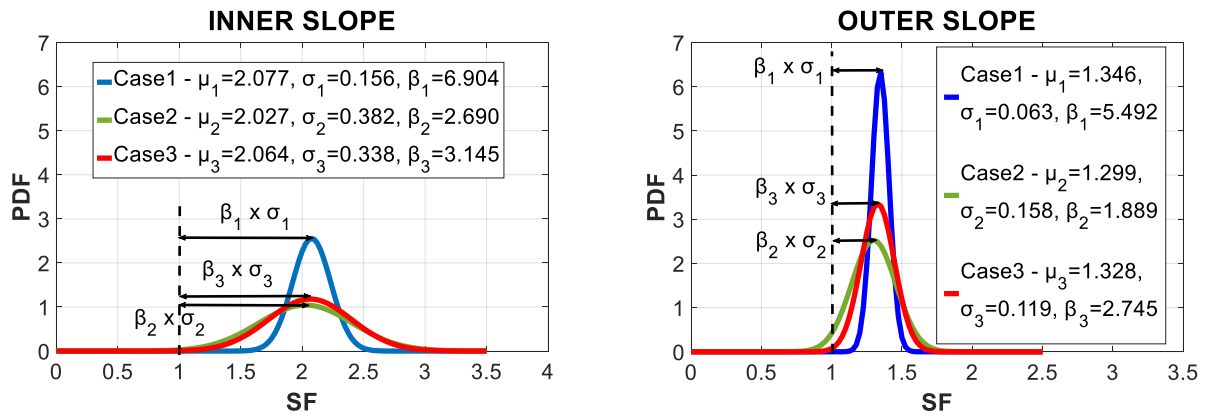
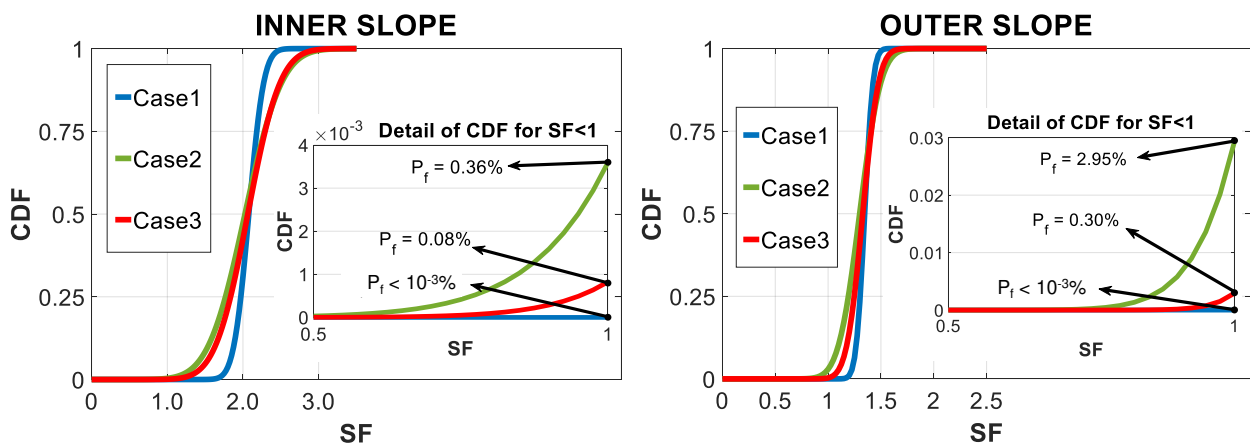


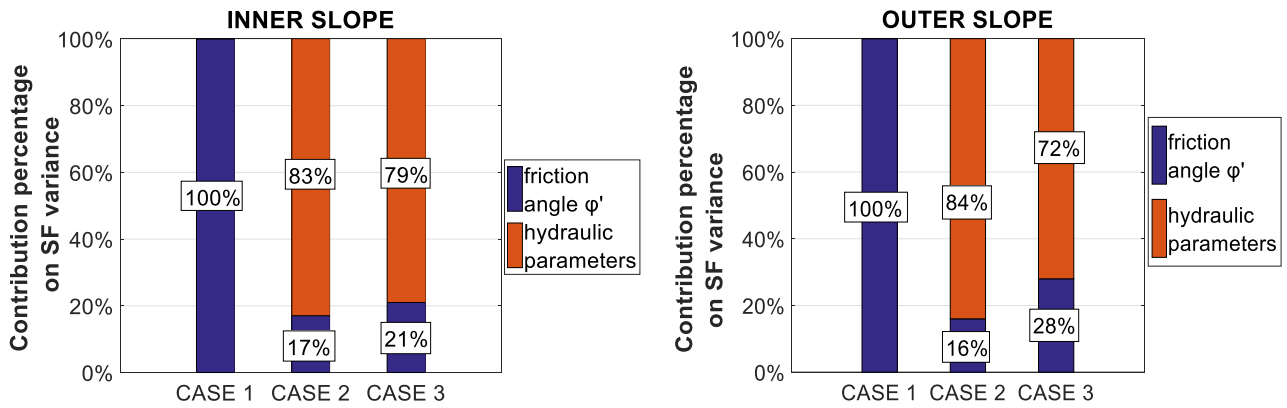
Figure 10 – Histogram of soil parameters with point estimate locations and relative weights.



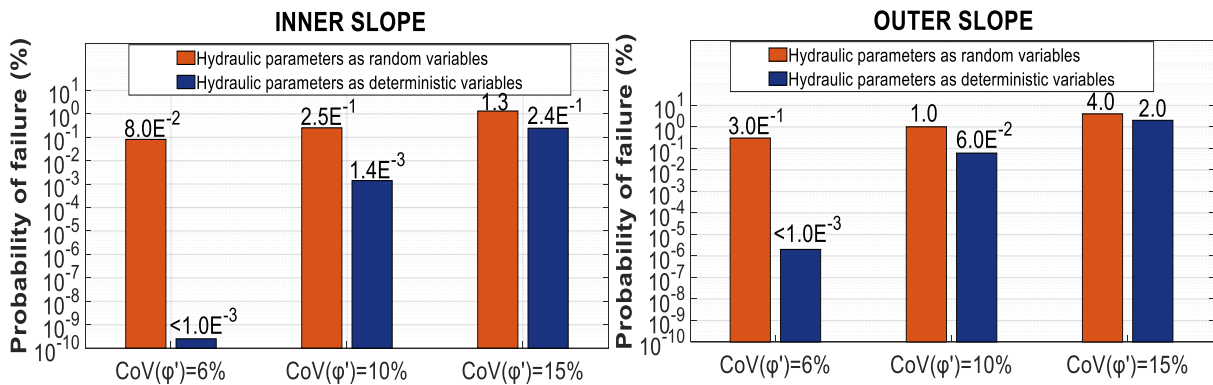
**Figure 11** – Probability density function (PDF) of the safety factor (SF) for both inner slope (left) and outer slope (right), for Case 1, Case 2 and Case 3, including the graphical estimate of the reliability index  $\beta$ .



**Figure 12** – Cumulative density function (CDF) of the safety factor (SF) for both inner slope (left) and outer slope (right), for Case 1, Case 2 and Case 3, including the graphical estimate of the probability of failure  $P_f$ .



**Figure 13** – Contribution of the hydraulic parameters and shear strength  $\phi'$  on the safety factor variance, for both inner slope (left) and outer slope (right).



**Figure 14** – Probability of failure vs. coefficient of variation of  $\phi'$ , for both inner slope (left) and outer slope (right), considering the hydraulic parameters as deterministic and as random variables.