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Citation for final published version:

Balzano, Brunella , Tarantino, Alessandro, Nicotera, Marco Valerio, Forte, Giovanni, De Falco, Melania and Santo, Antonio 2019. Building physically-based models for assessing rainfall-induced shallow landslide hazard at the catchment scale: the case study of the Sorrento Peninsula (Italy). *Canadian Geotechnical Journal* 56 (9) , pp. 1291-1303. 10.1139/cgj-2017-0611

Publishers page: <http://dx.doi.org/10.1139/cgj-2017-0611>

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## **Building physically-based models for assessing rainfall-induced shallow landslide hazard at the catchment scale: the case study of the Sorrento Peninsula (Italy)**

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## **Abstract**

The assessment of rainfall-induced shallow landslide hazard at the catchment scale poses significant challenge. Traditional empirical approaches for landslide hazard assessment often assume that conditions having caused failure in the past won't change in the future. This assumption may not hold in a climate change scenario. Physically-based models (PBMs) therefore represent the natural approach to include changing climate effects. PBMs would in principle require the combination of a 3-D mechanical and water-flow model. However, a full 3-D finite element model at the catchment scale, with relatively small elements required to capture the pore-water pressure gradients, would have a significant computational cost. For this reason, simplifications to the mechanical (i.e. infinite slope) and water-flow model (i.e. 1-D or hybrid 3-D) are introduced, often based on a-priori assumptions and not corroborated by experimental evidence. The paper presents a methodology to build a PBM in a bottom-up fashion based on geological surveys and geotechnical investigation. The PBM is initially set as simple as possible and then moved to a higher level of complexity if the model is not capable of simulating past landslide events. The approach is presented for the case study of Sorrento Peninsula and two main landslides events recorded during winter 1996-1997.

*Key words:* **Rainfall, Flow-like landslides, Unsaturated soil, Water flow**

## INTRODUCTION

1 Widespread rainfall-induced landslides are one of the major natural hazards and account for  
2 significant economic and human losses. The assessment of spatial and temporal landslide  
3 hazard at the catchment scale is the key to developing measures to mitigate landslide risk.

4 Landslide hazard can be quantified using empirical approaches. These are based on the  
5 correlation of historical records of landslide occurrence with either predisposition or  
6 triggering factors, which are leading to susceptibility maps (Andriola et al. 2009; Di  
7 Crescenzo et al. 2008; Godt et al. 2008; Wang et al. 2015) and rainfall thresholds (De Vita et  
8 al. 2002; Guzzetti et al. 2007) respectively. A major limitation of susceptibility maps is the  
9 identification of the factors predisposing the slopes to landsliding, which is based on intuitive  
10 understanding of the landslide mechanisms rather than catchment-specific physically-based  
11 models. On the other hand, empirical rainfall thresholds are generally based on a minimum or  
12 'safety' threshold for rainfall amounts and/or or intensity-duration that have produced  
13 landslides in the past. The conservative nature of the rainfall thresholds may lead to false  
14 alarm and the consequent loss of confidence in the early warning system ( Intrieri et al.  
15 2012). Overall, traditional empirical models are implicitly based on the assumptions that  
16 geomorphological and meteorological conditions having caused failure in the past will  
17 remain unchanged in the future. This assumption is not likely to hold in a climate change  
18 scenario.

19 These limitations can be overcome if landslide hazard is quantified via physically-based  
20 models. These combine a mechanical model for landslides initiation and a hydraulic model  
21 for rainwater infiltration. In principle, the analysis at the catchment scale involves 3-D  
22 stability analysis and 3-D water flow analysis. While 3-D analysis does not represent a  
23 challenge for individual landslides, the computational burden becomes prohibitive if the  
24 domain extends over kilometres and the pore-water pressure profile needs to be determined  
25 with a resolution of centimetres.

26 As a result, physically based models designed for catchment-scale analysis have been  
27 simplified in order to scale down the problem to 2-D or 1-D conditions. Indeed, the majority  
28 of the slope failure mechanical models are based the 1-D infinite slope (e.g. Simoni et al.  
29 2008; Godt et al. 2008; Papa et al. 2013, Aristizàbal et al. 2015).

30 On the other hand, various approaches are considered to model rainwater infiltration and  
31 lateral flow. A first class of models only consider saturated flow by neglecting the effect of  
32 the unsaturated upper part of the soil profile on the water redistribution mechanisms. These  
33 include SHALSTAB ( Montgomery and Dietrich 1994) and TRIGRS (Baum et al. 2002) and  
34 SHIA\_Landslide (Aristizabal et al., 2015). A second group takes into account unsaturated  
35 flow. Rigon et al. (2005) consider a hybrid 3-D water flow model by uncoupling lateral from  
36 vertical flow. However, the latter is modelled using a relatively coarse discretisation of the  
37 flow domain, which may not allow capturing the high pore-water pressure gradients that may  
38 develop during a rain-water infiltration process. Savage et al. (2004), Baum et al. (2010), and  
39 Papa et al. (2013) consider a 1-D vertical infiltration in order to implement closed-form  
40 analytical solutions for the water flow.

41 The common thread between these approaches is that the hydraulic model at the  
42 catchment scale is set-up a priori without consideration for the specific hillslope hydrology  
43 and landslide mechanisms actually characterising a specific area. The hydraulic model is  
44 intended to be 'universal' and therefore adapted to any catchment in a 'top-down' fashion.

45 This paper presents an alternative 'bottom-up' approach to the modelling of physically  
46 based models for rainfall-induced shallow landslides. The PBM is built from geological,  
47 geomorphological, and geotechnical investigation of historic landslide events. The  
48 physically-based model is initially set as simple as possible and then moved to a higher level  
49 of complexity if the model is not capable of simulating past landslide events. In other words,  
50 a one-dimensional scheme is initially adopted for both mechanical and hydraulic component  
51 of the physically-based model. This is then tested against historic landslide events. If the test  
52 is negative, the model is scaled-up to a higher level of complexity (e.g. 2-D flow).

53 The approach is illustrated with reference to the case study of the Sorrento Peninsula  
54 located in the Campania region in Southern Italy. Two historic landslides representative of the  
55 most typical soil profiles have been selected. The landslides are characterised as flow-like  
56 landslides (Hungre et al. 2014; Santo et al. 2018). The 'quality' of the physically-based model  
57 has been therefore assessed against its capability to reproduce the time of failure and the  
58 location of the slip surface identified by the geological survey following the landslide events.

59

## STUDY AREA

### 60 **Geological setting**

61 The study area is located on the Tyrrhenian coast of Campania. During the Plio-Quaternary  
62 times, important regional faults associated with the extension of the Tyrrhenian area  
63 generated a major tectonic depression named the Campania graben (Southern Italy). The  
64 structural horsts bounding this graben include the carbonate Sorrento Peninsula–Lattari  
65 Mountains, the Partenio Mountains, the Caserta Hills, Pizzo D’Alvano mountain, and  
66 Maggiore Mountain. These mountains consist of more than 1500-m-thick Mesozoic  
67 dolomites and limestones.

68 The most recent deposits on the limestone formation are quaternary continental debris and  
69 pyroclastic deposits; the latter are a few metres thick and associated with the Late  
70 Pleistocene–Holocene Plinian eruptions of the Campi Flegrei and Somma-Vesuvio volcanic  
71 areas. The fallout products of these volcanic areas were deposited mostly on the carbonate  
72 formation. Studies of the dispersion axis of pyroclastic deposits have shown that the most  
73 superficial layers (pumices and pyroclastic cover) in the area of the Sorrento Peninsula are  
74 associated with the AD 79 eruption.

75 The geomorphological pattern is characterized by high relief slopes, with peaks often  
76 reaching altitudes greater than 1000 m. In most cases, these slopes have been associated with  
77 fault scarps generated by various phases of block faulting that occurred during the late  
78 Pliocene and the lower and middle Pleistocene. Slope replacement then took place, producing  
79 linear slopes characterized by a rectilinear cross profile with a medium slope angle of about  
80 35° (Brancaccio et al. 1999). This morphological context affected the deposition of the  
81 Holocene pyroclastic fall deposits. The presence of pyroclastic covers, especially in the  
82 steeper areas, makes wide sectors of these slopes particularly susceptible to the triggering of  
83 debris slides–rapid earth flows. These are usually triggered by short duration intense  
84 meteorological events, particularly after prolonged periods of antecedent rainfall. Due to their  
85 high degree of fluidity they can travel over long distances, thereby increasing their power of  
86 destruction. Many landslides events took place in the past, very often with tragic  
87 consequences on goods and human lives.

### 88 **The landslide events of January 1997**

89 An intense period of precipitation occurred in Campania from January 9<sup>th</sup> to 11<sup>th</sup>, 1997.  
90 Rainfall was particularly intense in the western areas of the region, namely, the Sorrento  
91 Peninsula and the Lattari Mountains. A 3-day cumulative rainfall of about 280 mm was  
92 registered at those locations, preceded by a 4-month period of high cumulative rainfall. On  
93 the same days, several hundreds of landslides were triggered in the Campania region. Most of  
94 these landslides (about 400) occurred in the Sorrento Peninsula–Lattari Mountains.  
95 Landslides involving natural slopes were mainly superficial, sometimes turning into  
96 debris/earth flows. Small-scale falls and slides occurred on cut slopes (Di Crescenzo and  
97 Santo 1999).

98 This work deals with two events occurred on the 10<sup>th</sup> of January 1997: the Gragnano and  
99 Corbara’s landslides (Figure 1).

100

101

102           **Gragnano**

103   The Gragnano (1997) landslide was triggered on the northern slope of Pendolo Mt., an area  
104   severely affected by those events in the past. The area is characterized by a high grade of  
105   susceptibility, mainly due to high values of slope angles (around 35°) and a fair continuity of  
106   the pyroclastic material between 0.5 -2.5 m thick. The carbonate bedrock in the area is  
107   strongly fractured and karstified and it is covered by an ash-fall layer characterized by a high  
108   clay content (C1 and C2). The latter is covered by the products of 79 AD Plinian eruption, i.e.  
109   coarse pumices (B), ashes (A2) and soil (A1) as shown in Figure 2

110   This landslide event occurred around 1:30pm of the 10<sup>th</sup> of January 1997 and took place in an  
111   area affected by another previous event, activated at 9 am of the very same day (Figure 3a). It  
112   seems that before the major landslide events, the soil itself showed some premonitory cuts on  
113   its surface. The average length of the landslide is roughly 220 m, involving 4500 m<sup>3</sup> of  
114   material (Figure 3b).

115           **Corbara**

116   This event took place adjacent to the road that leads to the Chiunzi Pass and was  
117   characterised by a total length of 250m. It started as a translational shallow landslide that  
118   evolved into a debris flow. In this case, it was not possible to identify the soil profile at the  
119   landslide scarp due to remedial works that took place immediately after the event. The soil  
120   profile was characterised by boreholes and/or trenches out by the Geology Department of  
121   University of Naples Federico II just close to the landslide site and is shown in Figure 4. In  
122   this case, the bedrock appears to be covered by a very thin layer (0.3-0.4 m) of ashes,  
123   overlain by a 0.8-0.9 m layer of yellow pumices and a 0.9m layer of pedogenised pyroclastic  
124   soil.

## **MATERIALS**

125   Three major soil types cover the limestone bedrock (Figure 5):

- 126   • A top layer of pyroclastic soil, which has been affected by biogeochemical processes as a  
127   result of the direct and indirect action of microorganism and vegetation (A1). This layer  
128   originally formed during the last stage of the 79 AD eruption.  
129   • Pumices (P). This layer was deposited during the early stage of the 79 AD eruption.  
130   • Ashes, deriving from an ancient eruption (130000 years ago ca.) from Campi Flegrei  
131   volcanic areas (C1 and C2)

132   The hydro-mechanical characterisation of these soils was carried using different  
133   approaches depending on the layer in question. The choice hydro-mechanical properties of  
134   the layers A1, P, and C1 was based on the characteristics of similar soils at a site located in  
135   another area of the Campania region due to the similarity in terms of the grain-size  
136   distribution and volcanic origin (Monteforte Irpino, Figure 4). The hydraulic properties of  
137   the soils at the Monteforte Irpino site were indeed investigated extensively via laboratory  
138   testing and field monitoring (Pirone et al. 2015; Pirone et al. 2016). A typical soil profile at  
139   the Monteforte Irpino site is reported in Figure 6.

140   The hydraulic characterisation of soil C2 was carried out via laboratory testing of single  
141   sample taken from the C2 layer in the Sorrento Peninsula. This soil type is not present in the

142 Monteforte Irpino soil profile and, hence, its properties could not be borrowed from any of  
143 the soils at this site.

## 144 **Hydraulic Properties**

### 145 **Soil A1 and C1**

146 Figure 7 shows the comparison between the grain size distributions of Soil 1 from Monteforte  
147 Irpino and Soil A1 from the Sorrento Peninsula (a) and between Soil 6 from Monteforte  
148 Irpino and Soil C1 from the Sorrento Peninsula (b). Due to the similarity of the GSD, it was  
149 assumed that hydraulic and mechanical properties are also similar.

150 Figure 8a shows the water retention data derived from field measurements in Soil 1. The  
151 water retention curve has been represented with suction in linear scale. It represents the water  
152 retention behaviour up to saturation in the negative range of suction (positive range of pore-  
153 water pressure). The main drying and main wetting curves derived from laboratory  
154 measurements are also shown in the figure (Pirone et al. 2015). The field data lie between the  
155 main drying and main wetting curves, i.e. they appear to populate scanning paths. Since the  
156 field data tends to cover a relatively narrow region, water retention behaviour of Soil 1 was  
157 modelled via a single (scanning) curve. A modified Van Genuchten function (Van Genuchten  
158 1980) has been used to model the water retention behaviour for Soil 1.

$$\theta = \theta_r + (\theta_s - \theta_r)(1 + \alpha(u_w^* + s)^n)^{-(1-\frac{1}{n})} \quad [1]$$

159 here

- 160 •  $\theta_s$  is the volumetric water content at saturation
- 161 •  $\theta_r$  is the residual volumetric water content
- 162 •  $u_w^*$  is the value of (positive) pore water pressure at which the degree of saturation  
163 becomes equal to 1 ( $\theta = \theta_s$ )
- 164 •  $\alpha$  and  $n$  are fitting parameters

165 Figure 8b shows the field measurements of hydraulic conductivity for the Soil 1 (Pirone  
166 et al. 2015). For comparison, the hydraulic conductivity derived in the laboratory from  
167 undisturbed samples is also shown in the figure. The saturated hydraulic conductivity  
168 measured in the field appears to be higher than the one measured in the laboratory by one  
169 order of magnitude. This can be attributed to macro-porosities that are present in the field  
170 due to the effect of microbial activity and presence of roots in the rhizosphere. A modified  
171 Mualem-Van Genuchten function (Mualem 1976) has been used to model the hydraulic  
172 conductivity behaviour for Soil 1.

$$k = k_s S_r^l [1 - (1 - S_r^{n/n-1})^{1-\frac{1}{n}}]^2 \quad [2]$$

173 where

- 174 •  $k_s$  is the saturated hydraulic conductivity,
- 175 •  $S_r$  is the degree of saturation
- 176 •  $l$  is a fitting parameter

177 • n is the fitting parameter already introduced for Equation 1

178 Figure 9a shows the water retention data derived from field measurements in Soil 6. The  
179 main drying curve derived from laboratory measurements is also shown in the figure (Pirone,  
180 et al. 2015). By comparison with Figure 9a, it can be inferred that field data for Soil 6 also  
181 populate scanning paths. Equation 1 was also used to model the (scanning) water retention  
182 curve for Soil 6.

183 Figure 9b shows the unsaturated hydraulic conductivity function for Soil 6 as derived  
184 from laboratory testing on undisturbed samples (Pirone et al. 2016) and also the laboratory  
185 measurements of saturated hydraulic conductivity on a second series undisturbed samples.  
186 As field data for hydraulic conductivity of Soil 6 are not available, an assumption had to be  
187 made regarding the field scaling factor for the hydraulic conductivity (i.e. the ratio between  
188 the values of hydraulic conductivity in the field and the laboratory respectively).

189 It can be reasonably inferred that smaller number and size of macro-pores are present in  
190 C1 as compared to A1 due to reduced microbial activity and presence of roots. A scaling  
191 factor of 5 has therefore been used for Soil C1 as compared to the scaling factor of 10  
192 observed for Soil A1. The parameters used to model the soil A1 and C1 are reported in Table  
193 1.

#### 194 **Pumices**

195 The pumices layer present in the two sites of the Sorrento Peninsula originated during the  
196 eruption of Vesuvius in 79AD; these pumices appear to have a grain size distribution similar  
197 to that of soil layer 5 at the Monteforte Irpino site as shown by the comparison between the  
198 grain size distributions in Figure 10. However, soil layer 5 has been identified as a fall  
199 deposit produced by a more ancient eruption of Vesuvius (i.e. Avellino eruption 3760 b.p.).  
200 Evangelista et al. (2005) tested in the laboratory on reconstituted samples, along a main  
201 drying path, the water retention behaviour of Avellino pumices; in particular two tests were  
202 carried out, by considering the pumice particles initially dry or water-soaked.

203 Water retention appears to be bi-modal and was therefore modelled by considering the  
204 superposition of two Van Genuchten-type functions:

$$\mathcal{G} = \mathcal{G}_{res,l} + \frac{(\mathcal{G}_{sat,l} - \mathcal{G}_{res,l})}{\left(1 + (\alpha_l \cdot s)^{n_l}\right)^{m_l}} + \mathcal{G}_{res,h} + \frac{(\mathcal{G}_{sat,h} - \mathcal{G}_{res,h})}{\left(1 + (\alpha_h \cdot s)^{n_h}\right)^{m_h}} \quad [3]$$

205 Two sets of parameters should be assigned for the functions in the high and low range of  
206 suction respectively. In particular,  $\alpha_l, n_l, m_l$  and  $\theta_{sat,l}, \theta_{res,l}$  are the fitting parameters for the  
207 low range of suction and  $\alpha_h, n_h, m_h$  and  $\theta_{sat,h}, \theta_{res,h}$  are the fitting parameters for the high  
208 range of suction. The following constraints have to be imposed to liaise the parameters of the  
209 two functions with the overall volumetric water contents at saturation and at the residual  
210 state:

$$\vartheta_{sat,low} = \vartheta_{sat} - \vartheta_{res,low} \quad [4]$$

$$\vartheta_{sat,high} = \vartheta_{res,low} \quad [5]$$

$$\vartheta_{res,high} = \vartheta_{res} - \vartheta_{res,low} \quad [6]$$

211 The best-fitting parameters for the low and high suction range are reported in Table 3 and  
212 Table 4 respectively.

213 The saturated hydraulic conductivity of the Avellino pumice was available from  
214 laboratory measurements and found to be equal to 0.1 m/s.

215 Unfortunately, no experimental tests have been carried out to investigate the hydraulic  
216 conductivity in the unsaturated range. A very classical model was then considered for the  
217 hydraulic conductivity derived by combining the Mualem's model (Mualem, 1974) and the  
218 Brooks & Corey's model (Brooks & Corey's 1964)

$$K[m/sec] = K_{sat} \cdot \left(\frac{\vartheta}{n^*}\right)^{\frac{(2+2.5\lambda)}{\lambda}} \quad [7]$$

219 where  $\theta$  is the volumetric water content,  $n^*$  is the porosity, and  $\lambda$  is the slope of the water  
220 retention curve in a log-log plot. The parameter  $\lambda$  was tentatively derived by linearizing the  
221 bi-modal water retention curve as shown in Figure 11( $\lambda=0.273$ ).

## 222 **Soil C2**

223 The soil C2 could not be compared to any soil present at the Monteforte Irpino experimental  
224 site. For this layer, a single water retention test was performed on a single undisturbed sample  
225 taken from a site close to the landslides events. The water retention and hydraulic  
226 conductivity function were determined by inverse analysis of an evaporation process  
227 according to the approach presented by Nicotera et al. (2010). The curve determined  
228 experimentally was associated with a main drying path. According to Figure 12, a scanning  
229 path is likely to represent the water retention behaviour in the field more realistically than a  
230 main drying path. As a first approximation, the scanning path was derived by shifting the  
231 main drying water retention curve in order to have a degree of saturation at zero suction equal  
232 to 80% (rather than 100%) as shown in Figure 12a, similarly to what has been observed in  
233 soil A1 at the Monteforte Irpino site (Figure 6).

234 The hydraulic conductivity function was derived experimentally as a function of the  
235 degree of saturation according to Equation 1. The hydraulic conductivity function is shown in  
236 Figure 12b as a function of suction based on the 'scanning' water retention curve shown in  
237 Figure 12a.

238

## 239 **Mechanical Properties**

240 The shear strength properties for the soils A1, P, and C1, were again borrowed from the soils  
241 present at the Monteforte Irpino experimental site (associated with soils 1, 3, and 4  
242 respectively in Figure 6). Critical state values of friction angle reported in Table 5 have been

243 characterised by Papa (2008) and discussed by Sorbino and Nicotera (2013). For the soil C2,  
244 none of the soils present at the Monteforte Irpino experimental site have ‘identical’ grain-size  
245 distribution (as occurring for soils A1, P, and C1). The soil at Monteforte Irpino experimental  
246 site closest to C2 in terms of grain-size distribution and plasticity index is the Soil 8 in Figure  
247 6. The friction angle was therefore borrowed from this Soil 8 according to Papa (2008).

248 Finally, it was assumed that the saturated failure envelope is characterised by zero  
249 effective cohesion with the only exception of Soil A1 where a cohesion of 5 kPa was  
250 tentatively assigned to simulate root mechanical reinforcing.

251 The shear strength in the unsaturated range was formulated as follows according to  
252 Nicotera et al. (2015) as follows:

$$\tau = (\sigma + s \cdot S_r) \cdot \tan\phi' \quad [8]$$

253 where  $\sigma$  is the normal total stress  $s$  is the suction,  $S_r$  is the degree of saturation, and  $\phi'$  is the  
254 critical state friction angle.

## HYDRO-MECHANICAL MODEL

255 The two landslide events have been modelled numerically in order to reproduce the failure  
256 occurred on the 10<sup>th</sup> of January 1997 following heavy rainfall. Rain-water infiltration has  
257 been modelled assuming a rigid soil-skeleton (i.e. without considering any coupling with  
258 mechanical deformation). The onset of failure was modelled by assuming the soils to have a  
259 rigid-perfectly plastic behaviour

### 260 Hydraulic model

261 Rainwater infiltration within the slope was modelled using Darcy's law, extended to the case  
262 of unsaturated soils:

$$\vec{v} = -\mathbf{K} \text{grad}(\Psi) = -\mathbf{K} \text{grad} \left( z + \frac{u_w}{\gamma_w} \right) \quad [9]$$

263 where  $\vec{v}$  = flow velocity vector;  $\psi$  = piezometric head;  $\mathbf{K}$  = hydraulic conductivity;  $u_w$  = pore  
264 water pressure;  $\gamma_w$  = density of soil water; and  $z$  = vertical coordinate increasing upward. The  
265 hydraulic conductivity depends is a function of the pore water pressure.

266 The mass balance equation for liquid water can be written as follows:

$$\text{div } \vec{v} + \frac{\partial \theta}{\partial t} = 0 \quad [10]$$

267 where  $\theta$  = volumetric water content (ratio of water volume to total volume); and  $t$  = time. By  
268 substituting Equation 9 in Equation 10, the Richard's equation in terms of piezometric head is  
269 obtained:

$$C \frac{\partial \Psi}{\partial t} = \text{div}[\mathbf{K} \text{grad}(\Psi)] \quad [11]$$

270 where  $C = \gamma_w (\angle \theta / \angle u_w)$ , referred to as water capacity of the soil.

271 The volumetric water content  $\theta$  appearing in Equation 10 is given by:

$$\theta = n^* S_r \quad [12]$$

272 where  $n^*$  = porosity; and  $S_r$  = degree of saturation. In general,  $n^*$  depends on pore water  
273 pressure and, as a result, infiltration is coupled with the mechanical response of the soil.  
274 However, shallow landslides often occur in coarse-grained soils that have been subject to  
275 countless cycles of drying and wetting. Hence, it then appears reasonable to assume the soil  
276 skeleton to be incompressible with respect to pore water pressure changes. As a result, the  
277 problem of unsaturated flow can be uncoupled and Equation 11 can be used for calculating  
278 the change of pore water pressure with depth and time. The water flow Equation 11 was  
279 solved numerically via the FEM using the module SEEP/W of the software Geostudio.

280 **Geometry**

281 Rain-water infiltration has been modelled by tentatively assuming infinite slope ‘one-  
282 dimensional’ water flow. This assumption has then been tested as explained later in the paper.  
283 It will be shown that the 1-D model is appropriate for the slopes in question. However, if the  
284 test had been negative, a 2-D numerical model would have been considered in a second  
285 iteration. The soil profiles have been modelled accordingly to the stratigraphy reported in  
286 Figure 13.

287 **Boundary Conditions**

288 The boundary conditions for the numerical model are schematized in Figure 14 and consist  
289 of:

- 290 • Water inflow imposed at the top boundary (to simulate rainfall)
- 291 • Water outflow at 10 cm below the ground surface (to simulate evapotranspiration  
292 from the root system)
- 293 • Impermeable bottom boundary (to simulate the bedrock)

294 *Rainfall data*

295 Rainfall data were taken from rain gauges as close as possible to the landslide areas. Figure  
296 15a-b show the rainfall registered from the 1<sup>st</sup> of January 1994 until the 31<sup>st</sup> of January 1997  
297 for Gragnano and Corbara respectively.

298 *Potential evapo-transpiration*

299 The evapo-transpiration fluxes in the energy-limited regime (potential evapo-transpiration)  
300 were calculated using the Penmann-Monteith equation (Monteith, 1965)

$$ET_0 = \frac{\Delta(1 - \alpha)R + \rho_a c_p e_s \frac{(1 - RH)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad [13]$$

301 where

- 302 •  $\Delta$  is the slope of the saturated vapour pressure curve ( $\delta e_0 / \delta T$ , where  $e_0$  = saturated vapour  
303 pressure (kPa) and  $T_{\text{mean}}$  = daily mean temperature ( $^{\circ}\text{C}$ ))
- 304 •  $R$  is the (short wave) radiation flux
- 305 •  $\alpha$  is the albedo assumed to be equal to 0.23 according to Allen et al. (1998)
- 306 •  $\gamma$  is the psychrometric constant ( $\text{kPa } ^{\circ}\text{C}^{-1}$ ) given by  $0.665 \cdot 10^{-3} P$  where  $P$  is the  
307 atmospheric pressure (kPa)
- 308 •  $\rho_a$  is the air density
- 309 •  $c_p$  is the specific heat of dry air, assumed  $1.013 \cdot 10^{-3}$  ( $\text{MJ kg}^{-1} \text{ } ^{\circ}\text{C}^{-1}$ ),
- 310 •  $e_s$  is the mean saturated vapour pressure
- 311 •  $r_a$  is the bulk surface aerodynamic resistance for water vapour
- 312 •  $RH$  is the ambient relative humidity
- 313 •  $r_s$  is the canopy surface resistance

314 The aerodynamic resistance  $r_a$  was in turn modelled according to Allen et al. (1998)

$$r_a = \frac{\ln \left[ \frac{z_m - d}{z_{om}} \right] \ln \left[ \frac{z_h - d}{z_{oh}} \right]}{k^2 u_z} \quad [14]$$

315 where

- 316 •  $z_m$  height of wind measurements (m),
- 317 •  $z_h$  height of humidity measurements (m),
- 318 •  $d$  zero plane displacement height (m),
- 319 •  $z_{om}$  roughness length governing momentum transfer (m),
- 320 •  $z_{oh}$  roughness length governing transfer of heat and vapour (m),
- 321 •  $k$  von Karman's constant, 0.41 (-),
- 322 •  $u_z$  wind speed at height  $z$  ( $\text{m s}^{-1}$ ).

323 and the canopy resistance  $r_c$  was assumed equal to  $50 \text{ s m}^{-1}$  according to the value suggested  
 324 by Abteu et al. (1995) for the family of chestnuts.

325 The radiation  $R$ , the relative humidity  $RH$ , the temperature  $T$ , and wind speed  $u$  were  
 326 taken from an open access database ([www.ilmeteo.it](http://www.ilmeteo.it) for temperature, relative humidity, and  
 327 wind speed and [www.solaritaly.enea.it](http://www.solaritaly.enea.it) for solar radiation). The albedo  $\alpha$  was assumed equal  
 328 to 0.15 according to Oke (1992). The monthly evapo-transpiration fluxes calculated using Eq.  
 329 [9] are shown in Figure 16 for both the sites of Gragnano and Corbara.

### 330 *Water-limited evapo-transpiration*

331 Potential evapotranspiration only occurs if the soil-plant system can deliver the water flow  
 332 demanded by the atmosphere. For the case of high potential evapotranspiration rate and/or  
 333 low soil moisture content, this condition cannot be met and the actual water outflow is  
 334 dictated by soil-plant system rather than the meteorological conditions (water-limited  
 335 regime).

336 The reduction of water outflow in the water limited regime can be modelled via a  
 337 reduction function that relates the ratio between actual and potential evapotranspiration to the  
 338 suction at the water extraction. Figure 17 shows a typical reduction function as suggested by  
 339 Feddes et al.(1978). As shown, as long as the suction values stay lower than  $s_0$ , the system is  
 340 able to accommodate the atmospheric demand (actual evaporation = potential evaporation).  
 341 When the suction reaches the value  $s_0$ , the system's water storage is not sufficient to  
 342 accommodate the potential evapotranspiration any more. Therefore, for  $s > s_0$ , the actual  
 343 evaporative flux decreases until the system is completely dry ( $s = s_1$ ).

344 An approach was developed in this work to calibrate the parameters of the reduction  
 345 function, the suction value  $s_0$  and the slope of the reduction function  $\delta$ . A soil column 1.6 m  
 346 high characterised by the same soil profile at the Gragnano landslide site (Figure 13a) was  
 347 considered. The column was subjected to the boundary condition derived from Eq. 13 for the  
 348 period starting 01/01/1995.

349 Two different initial hydrostatic conditions, associated with suction at the base of the  
 350 column equal to 0 and 10 kPa respectively, were considered. Figure 18a shows the evolution  
 351 of suction at the top of the column over time. It can be seen that suction tends to increase very

352 rapidly after a period of time, which depends on the initial condition. The very rapid increase  
353 of suction is associated with the attainment of the water-limited regime; the soil column is no  
354 longer able to deliver the 8mm/day imposed at the boundary.

355 Figure 18b shows the time derivative of suction with respect to suction. It can be  
356 observed that i) time derivative is now independent of the initial condition and ii) the suction  
357 marking the transition to the water limited regime can be clearly identified. The suction of  
358 1000 kPa has been chosen for  $s_0$ .

359 To characterise the water limited regime, the assumption has been made that suction at  
360 the extraction point remains constant in the water limited regime. This assumption is built  
361 upon the observation that suction in the leaves tends to remain constant in the water-limited  
362 regime (Duursma et al. 2008). The parameter  $\delta$  was then selected by trial and error in order to  
363 reproduce a constant value of suction in the water limited regime as shown in Figure 19. The  
364 reduction function calibrated on the Gragnano soil profile is shown in Figure 20.

### 365 Initial Condition for the transient analysis

366 The landslide events occurred on the 10 January 1997. The numerical analysis of water flow  
367 was then carried out between 1 January 1996 and 28 February 1997. The numerical analysis  
368 requires an assumption about the initial condition in terms of pore-water pressure profile at  
369 the start of the analysis (1 January 1996). This initial condition is unknown and cannot be  
370 assumed a priori due to its significant influence on the numerical results, i.e. the slope may or  
371 may not experience failure in the numerical simulation depending on the (arbitrary) choice of  
372 the initial hydraulic condition.

373 An approach was then developed in this work to derive the initial hydraulic condition. Since  
374 the same approach is also used to test and validate the hydraulic model, it is discussed  
375 separately in the following section.

### 376 Validation of the hydraulic model

377 A distinct numerical analysis was carried out by considering rainfall and evapotranspiration  
378 occurring in 1994 and 1995 and repeating the same rainfall and evapotranspiration pattern for  
379 three times for Gragnano (for a total of 6 years) and for 1 time for Corbara (for a total of 2  
380 years). Three steady-state 'infinite slope' initial conditions were selected, assuming that  
381 suction at the bottom of the soil profile was equal to 10 kPa, 40 kPa and 100 kPa respectively.

382 The results from this analysis are shown in Figure 21 in terms of suction at the bottom  
383 boundary versus time. It can be observed that:

- 384 i) The effect of the (arbitrary) initial condition is eventually cancelled if the water  
385 flow analysis is carried out for a time sufficiently long (after about 4 years for  
386 Gragnano and 0.2 years for Corbara).
- 387 ii) Once the suctions generated by the three different initial conditions converge,  
388 suction tends to fluctuate around an average value that tends to remain constant  
389 over time.

390 Condition i) allows selecting the initial condition in an unambiguous way. Once  
391 convergence has occurred, the time evolution of suction over 1995 can be assumed to be the  
392 actual one. As a result, the suction profile at 31/12/1995 can be assumed as the initial  
393 condition for the analysis to be carried out for the period 01/01/1996 to 28/02/1997.

394 The condition ii) can be taken as an evidence of the robustness of the hydraulic model  
 395 assumed in terms of boundary conditions. In fact, one would expect that a hydrological  
 396 balance is accomplished over a relatively long period. If the hydraulic model (including its  
 397 boundary conditions) is not set properly, it may occur that the slope becomes either  
 398 oversaturated or entirely dry over time. In this case, it appears that the 1-D ‘infinite slope’  
 399 hydraulic model is appropriate for the slopes of Corbara and Gragnano. Should the test on  
 400 hydrological balance have failed, a different model should have been selected (e.g. 2-D) and  
 401 the iteration started again.

## 402 **Mechanical model**

### 403 **Geometry**

404 The length L and depth D of the landslides at the release zone measured during the  
 405 geomorphological survey after the landslide event are reported in Table 7. It can be observed  
 406 that the ratio D/L is less than 1/10 and the onset of failure was therefore modelled by  
 407 assuming an ‘infinite slope’ failure mechanism.

### 408 **Factor of safety**

409 The factor of safety at any depth can be derived via the limit equilibrium method. By  
 410 considering the shear strength criterion given by Equation 15, the following equation can be  
 411 derived

$$412 \text{ FoS} = \frac{\tan\phi'}{\tan\beta} + \frac{-u_w S_r \cdot \tan\phi'}{(\bar{\gamma}H) \cdot \sin\beta \cdot \cos\beta} \quad [15]$$

412 where H is the depth of the failure surface,  $\beta$  is the inclination of the slope, and  $\bar{\gamma}$  is the  
 413 average unit weight given by:

$$414 \bar{\gamma} = \frac{1}{H} \int_0^H [\gamma_s(1 - n^*) + \gamma_w n^* S_r] dz \quad [16]$$

414 where  $\gamma_s$  and  $\gamma_w$  are the unit weight of solids and water respectively, and  $n^*$  is the porosity.

## **RESULTS**

415 To derive the factor of safety versus time, the water flow equation (Eq. 11) was first solved  
 416 numerically considering the hydraulic properties, initial condition, and boundary conditions  
 417 discussed in the previous section. In particular, the water retention and hydraulic conductivity  
 418 functions shown in Figure 8, Figure 9, Figure 11 and Figure 12 were considered for the  
 419 materials forming the slope as shown in Figure 13. The boundary conditions shown in Figure  
 420 14 and discussed in the “Hydro-mechanical Model” Section were considered.

421 Figure 22 shows the evolution of the Factor of Safety (FoS) for the case studies analysed  
 422 from 1 January 1996 until the day where a FoS equal to unity was attained at one depth at  
 423 least. To highlight the evolution of the FoS, Figure 23 shows the evolution of the minimum  
 424 FoS from January 1996 to the 10th of January 1997 when the landslide events occurred

425 The numerical simulation returned failure conditions on the 12 January 1997 for the case  
426 of Corbara (progressive day no. 377) and 11 January 1997 (progressive day no. 376) for the  
427 case of Gragnano. These times compare favourably well with the date of 10 January 2017  
428 where landslides occurred. It is also worth observing that the numerical simulation returns a  
429 failure surface developing at the interface between C1 and C2 for Gragnano and at the  
430 interface between C1 and the bedrock for Corbara. Again, this is consistent with the field  
431 observation following the survey after the landslide event. Overall, these results returned by  
432 the numerical simulation corroborate the approach adopted to formulate the physically-based  
433 hydro-mechanical model for the two landslides.

434 To have a better insight into the hydrological mechanisms triggering the landslides in the  
435 Sorrento Peninsula, it is worth exploring the pore-water profiles at the time of failure as  
436 shown in Figure 24. A sharp change in hydraulic conductivity occurs at the interface between  
437 the ashes (C1) and the compacted ashes (C2) for the case of Gragnano (a) and at the interface  
438 between the ashes (C1) and the bedrock for the case of Corbara (b). This causes the formation  
439 of a perched water table as inferred from the positive pressure generated above the C1-C2  
440 interface for Gragnano and C1-Bedrock for Corbara. Positive pore-water pressures then cause  
441 a drop in normal effective stress and, hence, shear strength until failure is eventually  
442 triggered.

## CONCLUSIONS

443 This paper has presented an approach to formulate physically-based models for shallow  
444 landslides. The model was built in a ‘bottom-up’ fashion based on geological,  
445 geomorphological, and geotechnical investigation of historic landslides.

446 These investigations allowed designing typical soil profiles and characterising  
447 mechanically and hydraulically the materials forming the different geological layers present  
448 in the area. The hydraulic model was then tentatively set as one-dimensional and tested  
449 against i) its ability to reproduce a satisfactory hydrologic balance over a relatively long  
450 period with the slope subjected to real rainfall and evapotranspiration pattern and ii) its  
451 capability of losing memory of the initial condition inevitably set up in an arbitrary fashion.  
452 The hydrological balance was considered as a ‘hypothesis test’ for the hydraulic model. If the  
453 test is positive, which was the case for the shallow slopes considered in this study, there will  
454 be no need to develop more sophisticated (and computationally expensive) hydraulic models  
455 in two or three dimensions. This clearly simplifies the numerical modelling of the landslide  
456 initiation at the catchment scale. At the same time, the use of a hydraulic 1-D model could be  
457 corroborated by numerical evidence and was not cast a-priori as often the case in numerical  
458 studies of shallow landslide initiation at the catchment scale reported in the literature.

459 The hydraulic model (including its boundary and initial conditions) was then coupled  
460 with a simple mechanical model and tested against its capability of reproducing the time of  
461 failure and the location of the slip surface identified by the geological survey following the  
462 landslide events. Again, this was taken as ‘hypothesis test’ for the hydro-mechanical  
463 physically-based model for the Sorrento Peninsula catchment.

464 The model has shown to adequately capture time and location of failure for the two  
465 historical landslide events considered. This makes it possible to generalise the physically-

466 based model to the entire catchment with fair confidence and use is as a basis to develop  
467 hazard maps and/or hydrological triggering thresholds used in early-warning systems.

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Soil	$\theta_s$ -	$\theta_r$ -	$S_{res}$ -	$u_w^*$ kPa	$\alpha$ 1/kPa	$n$ -	$m$ -	$l$ -	$k_s$ m/s
A1	0.62	0.17	0	7	0.05	1.7	0.41	-1	$3.4 \cdot 10^{-5}$
C1	0.67	0.198	0.065	7	0.015	1.7	0.41	-2.7	$1.7 \cdot 10^{-6}$

**Table 2. Hydraulic Parameters for the soil C2**

$\theta_s$ -	$\theta_r$ -	$\alpha$ 1/kPa	$n$ -	$m$ -	$\lambda$ -	$k_s$ m/s
0.517	0.018	0.005	1.07	0.0654	0.273	$5 \cdot 10^{-8}$

**Table 3. Hydraulic parameters for the pumices in the low suction range.**

$\vartheta_{sat,low}$ -	$\vartheta_{res,low}$ -	$\alpha_l$ 1/kPa	$n_l$ -	$m_l$ -
0.63	0.12	0.63	3	0.67

**Table 4. Hydraulic parameters for the pumices in the high suction range.**

$\vartheta_{sat,high}$ -	$\vartheta_{res,high}$ -	$\alpha_h$ 1/kPa	$n_h$ -	$m_h$ -
0.12	-0.12	0.02	2	0.5

**Table 5. Mechanical properties for the soils.**

SOIL	$\gamma_{dry}$ kN/m <sup>3</sup>	$\phi'$ °	$n^*$ -	$G_s$ -	$c'$ kPa
A1	8.06	37	0.69	2.65	5
C1	7.09	37	0.72	2.64	0
C2	10.64	37	0.57	2.49	0
P	4.8	40	0.8	2.55	0

**Table 6. Geometric characteristics of the landslides under study.**

<b>LOCATION</b>	<b>Length</b> <i>m</i>	<b>Depth</b> <i>m</i>	<b>D/L</b>
Gagnano	18	1.6	0.09
Corbara	24	2.3	0.096



# FIGURES

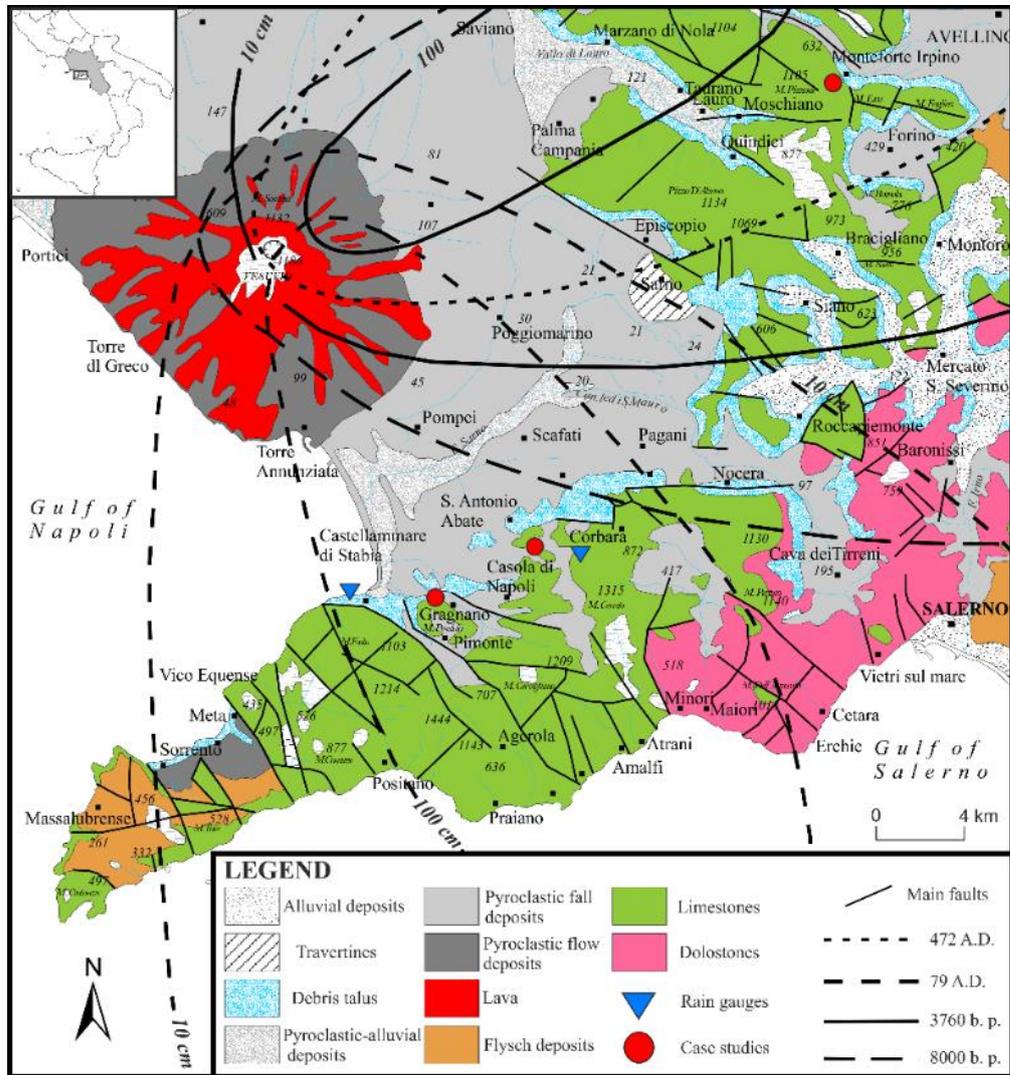


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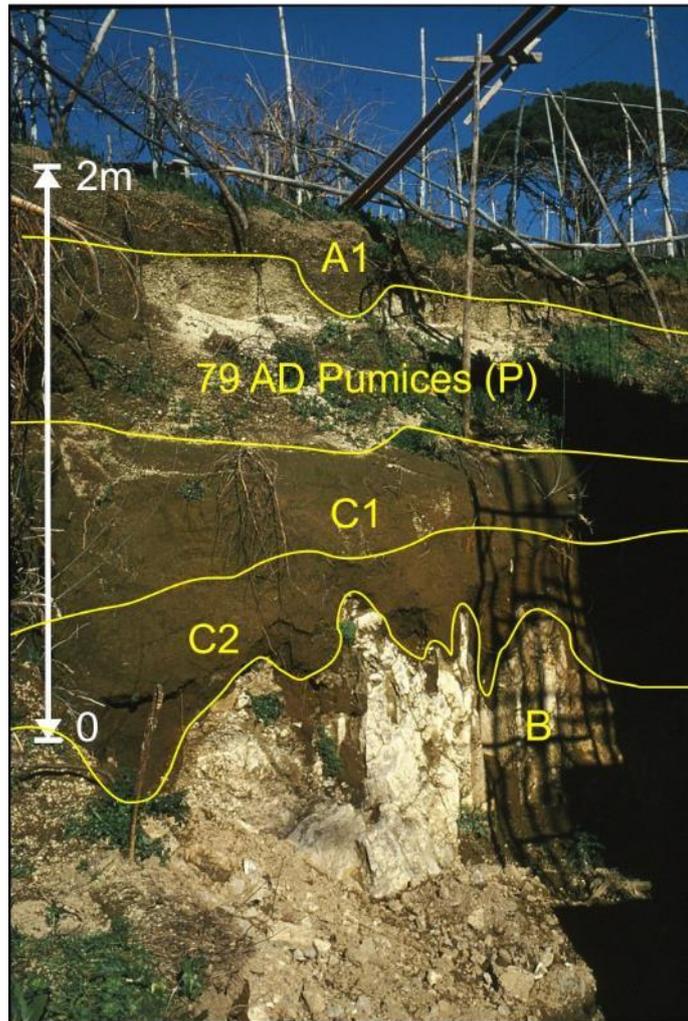


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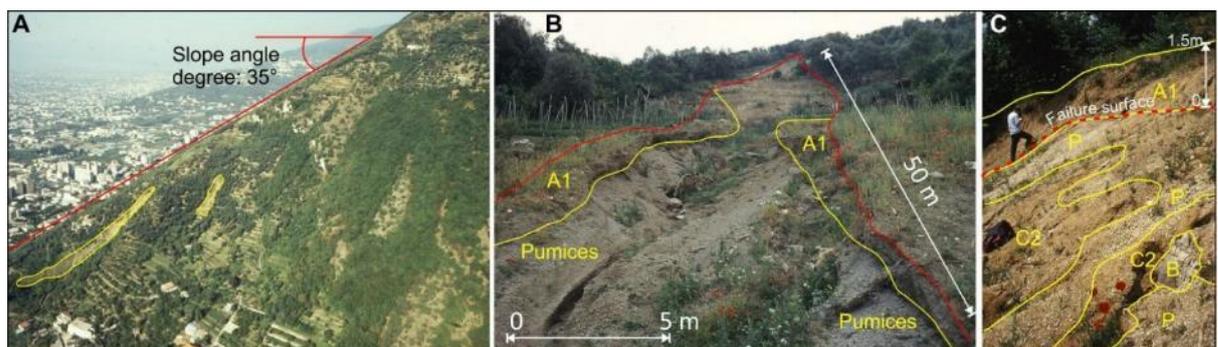


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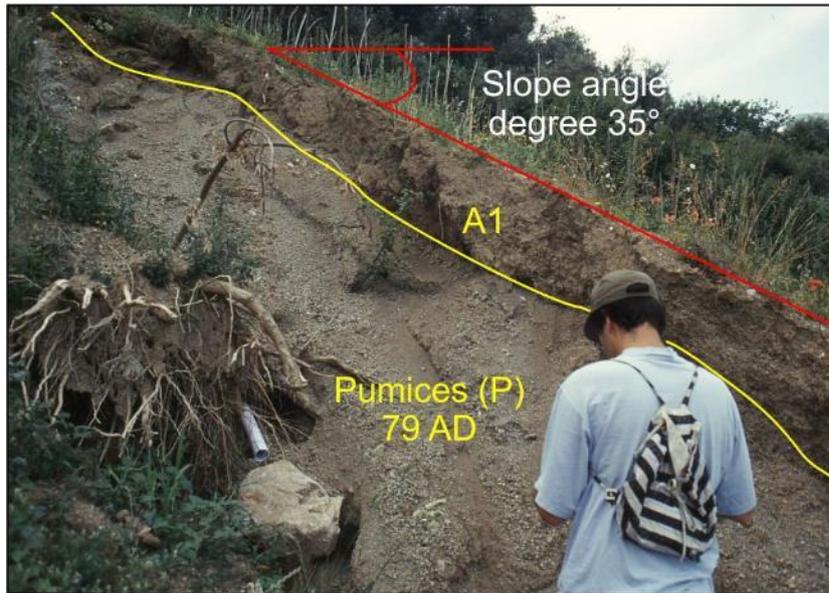


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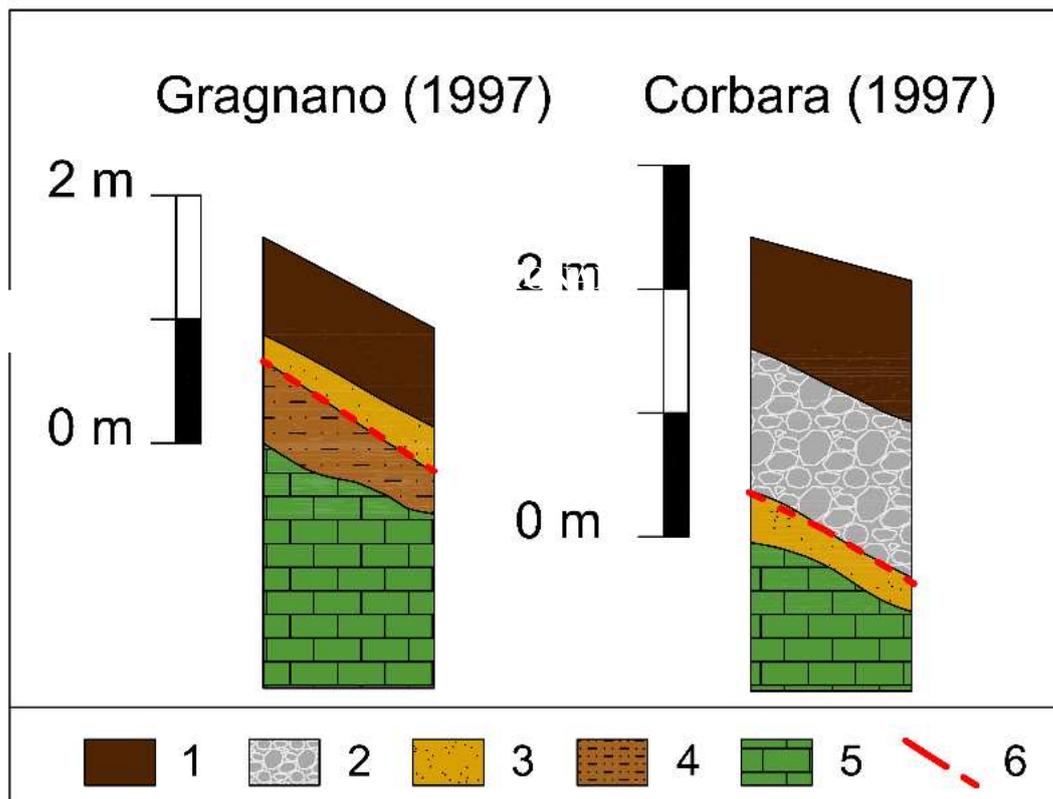
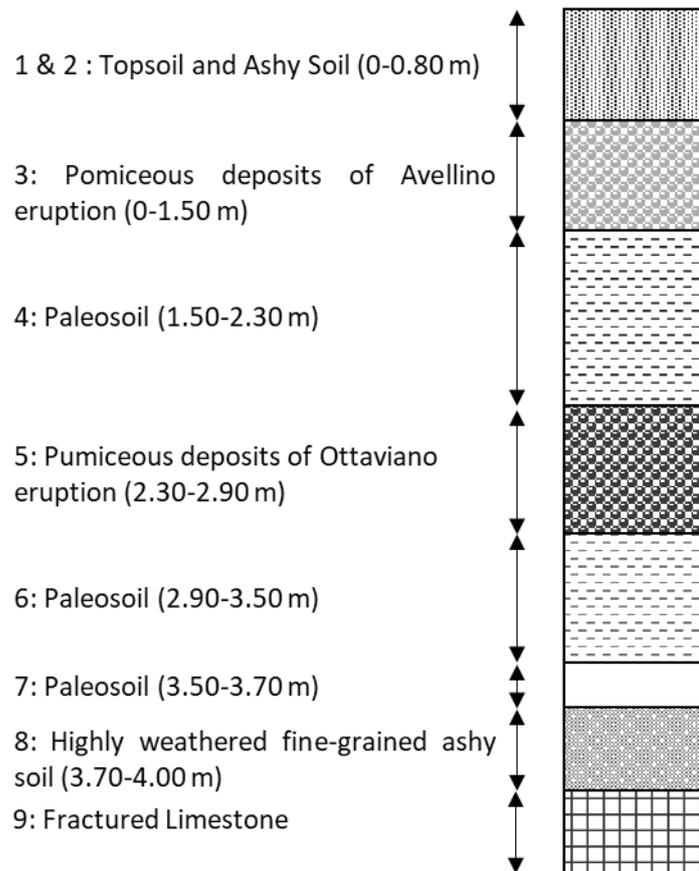


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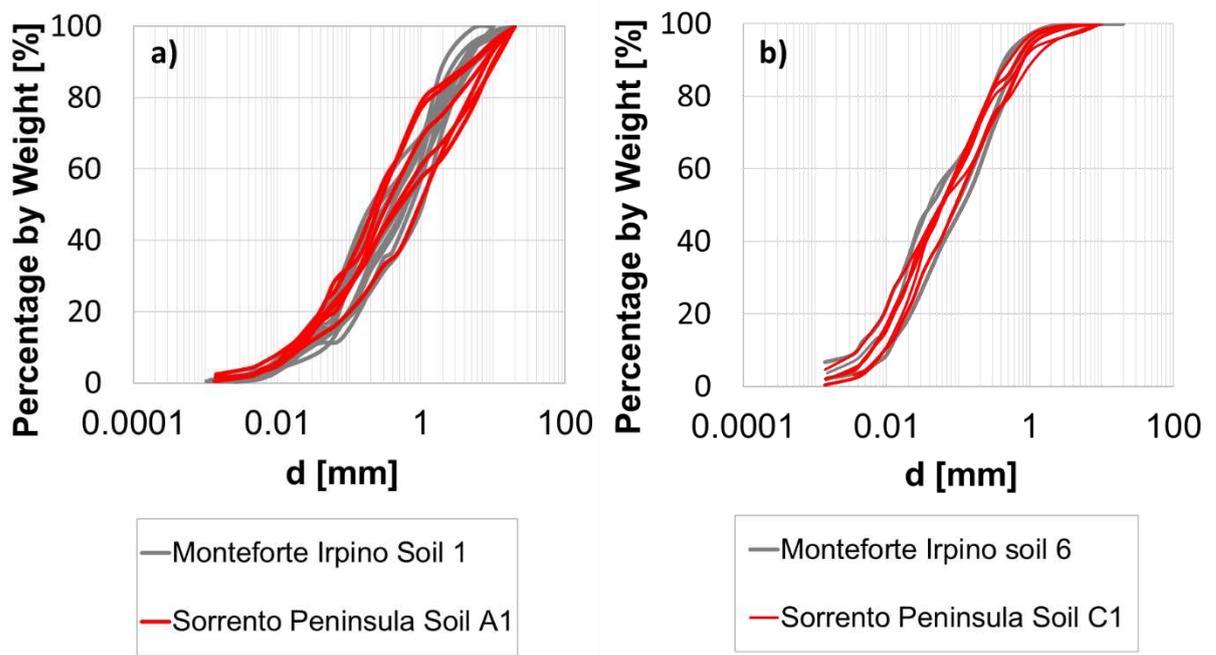


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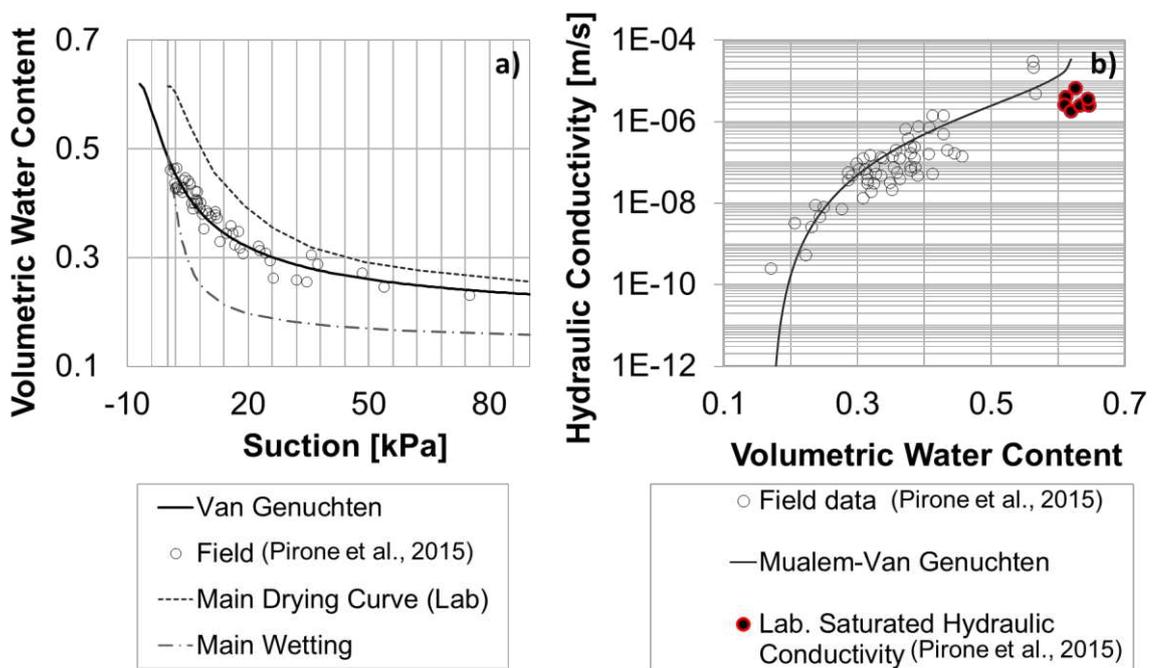
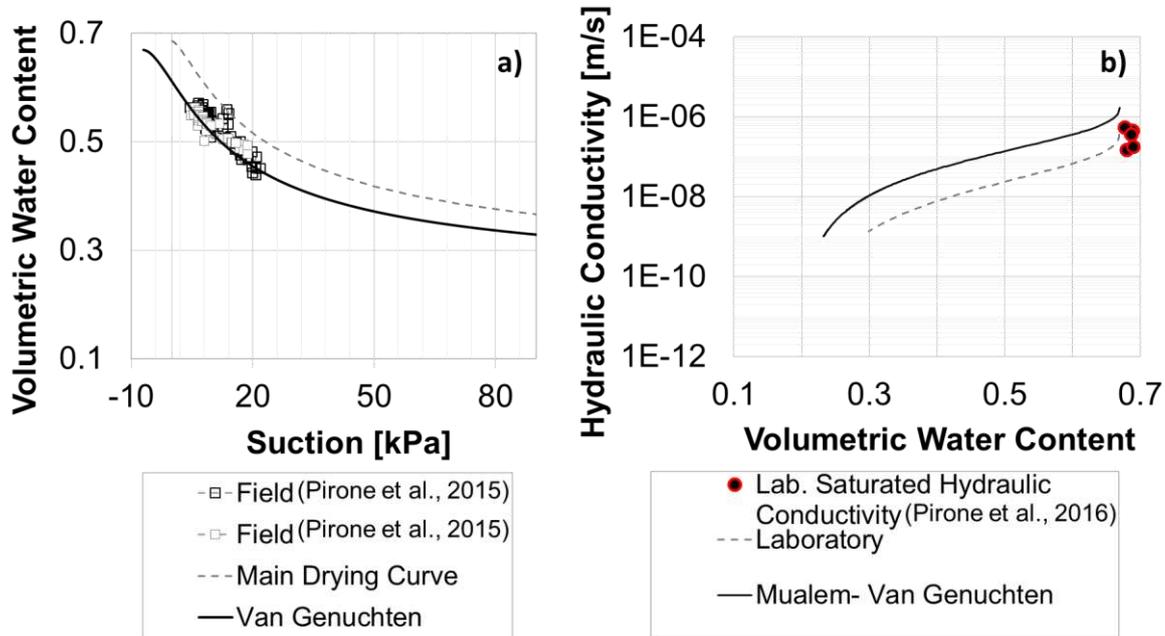


Figure 8. Water retention curve (a) and hydraulic conductivity (b) of the soil A1.



**Figure 9. Water retention curve (a) and hydraulic conductivity (b) of the soil C1.**

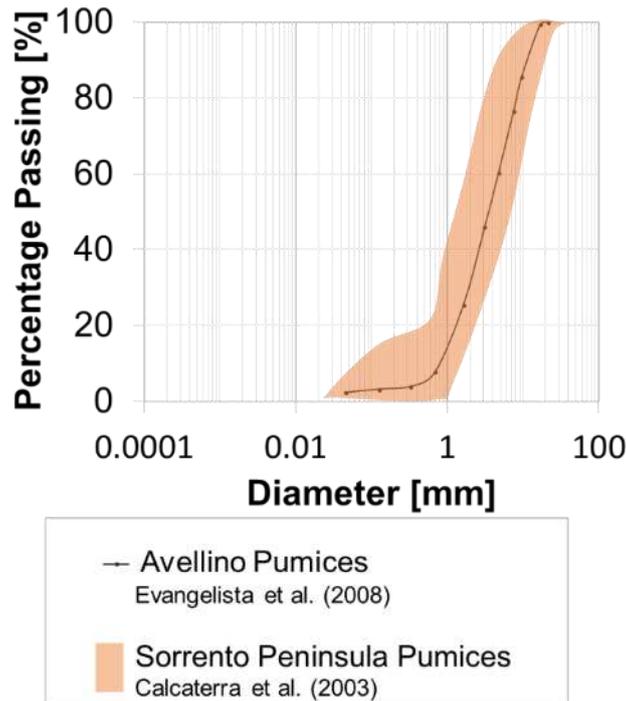


Figure 10. Comparison Grain size distribution of Sorrento Pumice and Avellino Pumice.

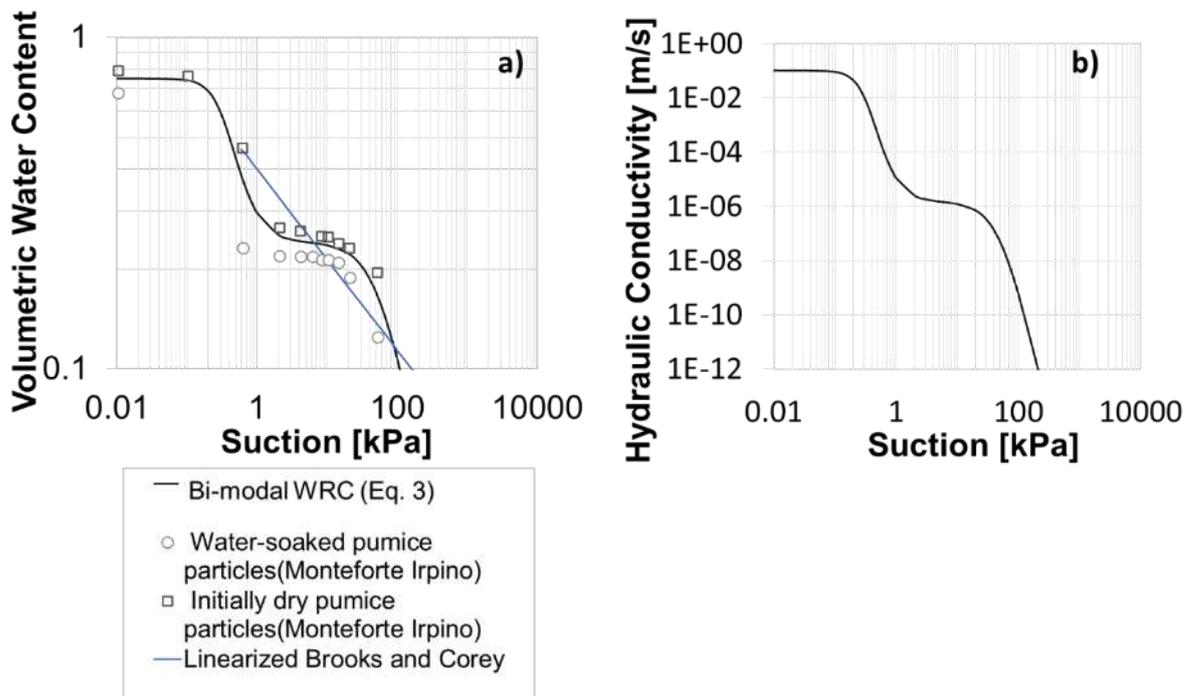


Figure 11. Water retention curve (a) and Hydraulic Conductivity Curve (b; Equation 4) for the pumices.

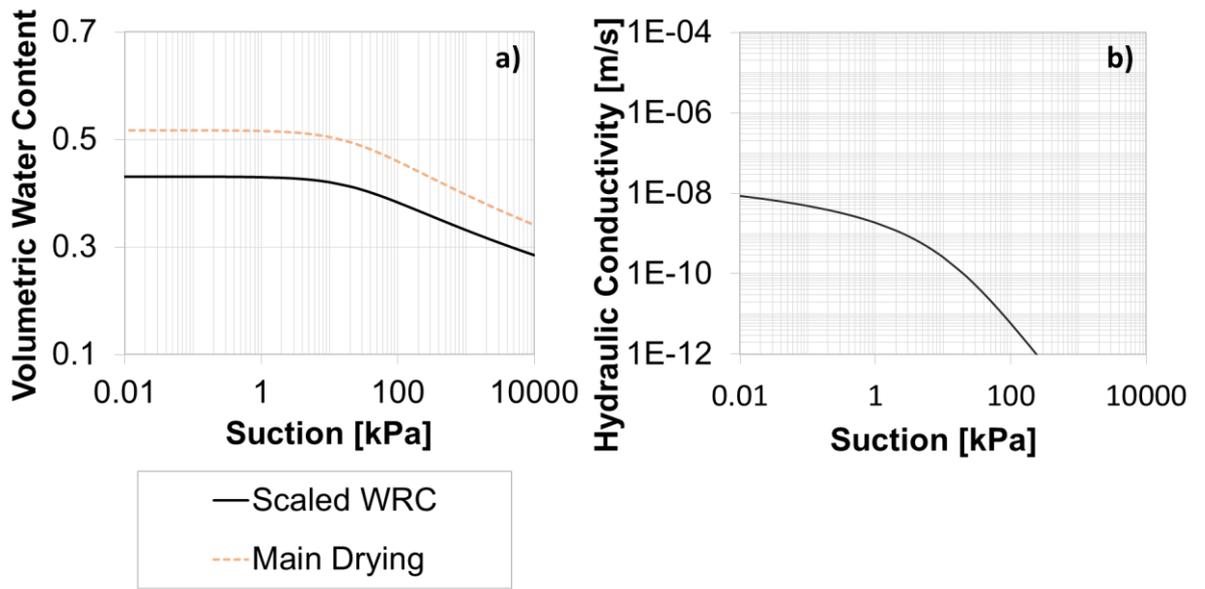
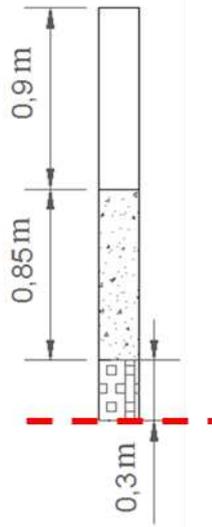
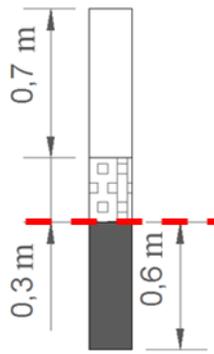


Figure 12. Water retention curve (a) and Hydraulic Conductivity (b) of the soil C2.



**GRAGNANO**

**CORBARA**

-  Pedogenized Pyroclastic Soil (A1)
-  Bedrock
-  Ashes (C1)
-  Compacted Ashes (C2)
-  Pumices (P)
-  Failure Surface

**Figure 13. Soil profiles adopted in the analyses.**

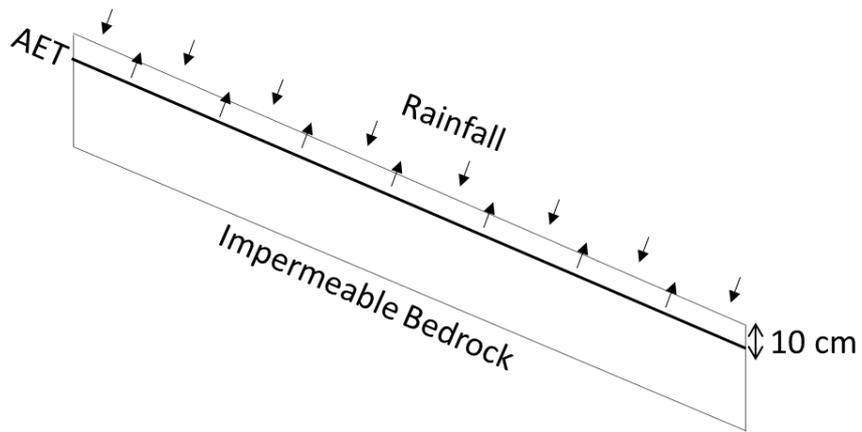


Figure 14. Scheme of the Boundary Conditions considered for the model.

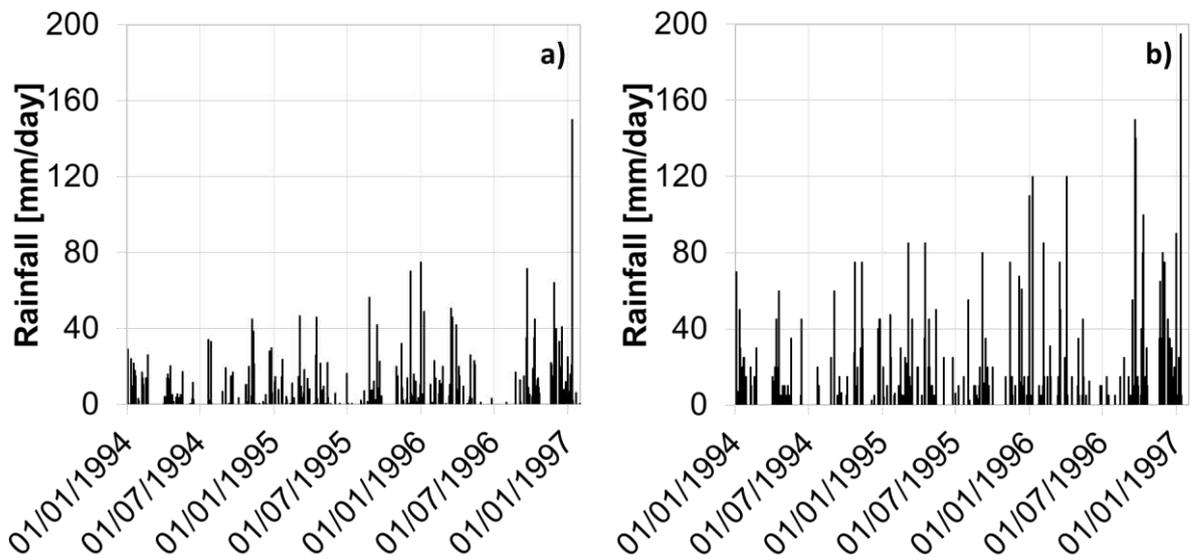


Figure 15. Rainfall from 1994 to 1997 registered by the pluviometer in Castellammare di Stabia (a) and Tramonti (b).

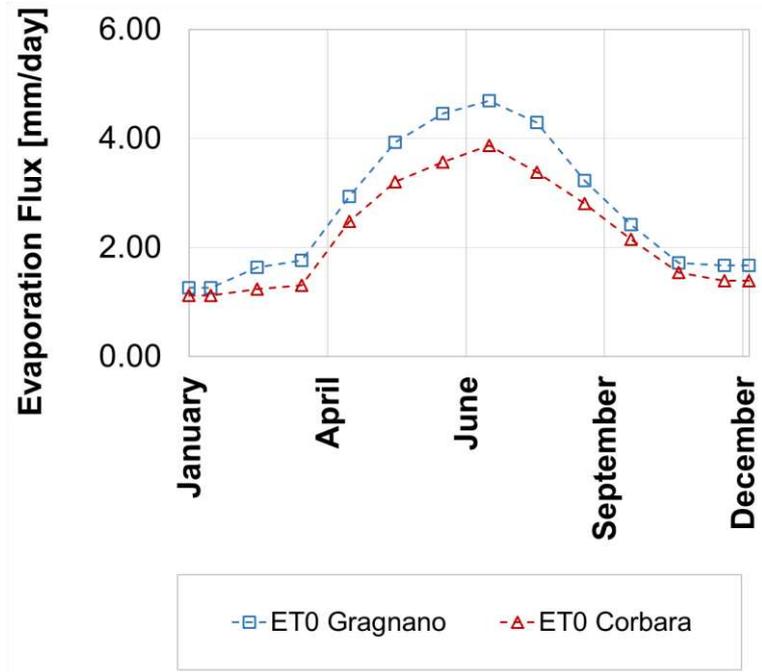


Figure 16. Monthly evaporation fluxes for Gragnano and Corbara.

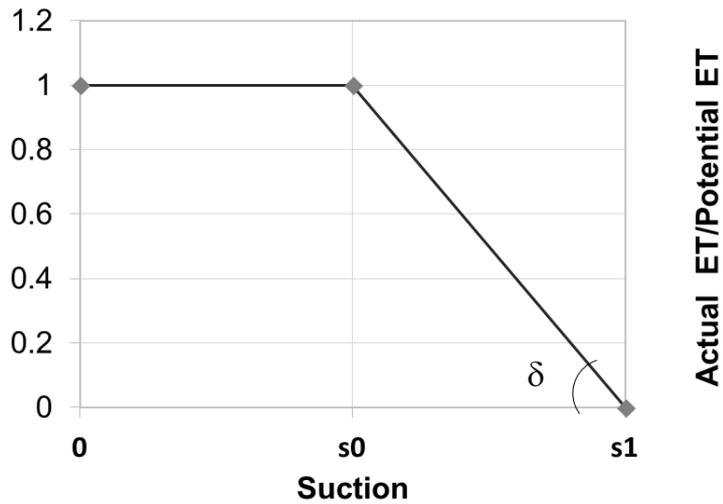


Figure 17. Reduction function

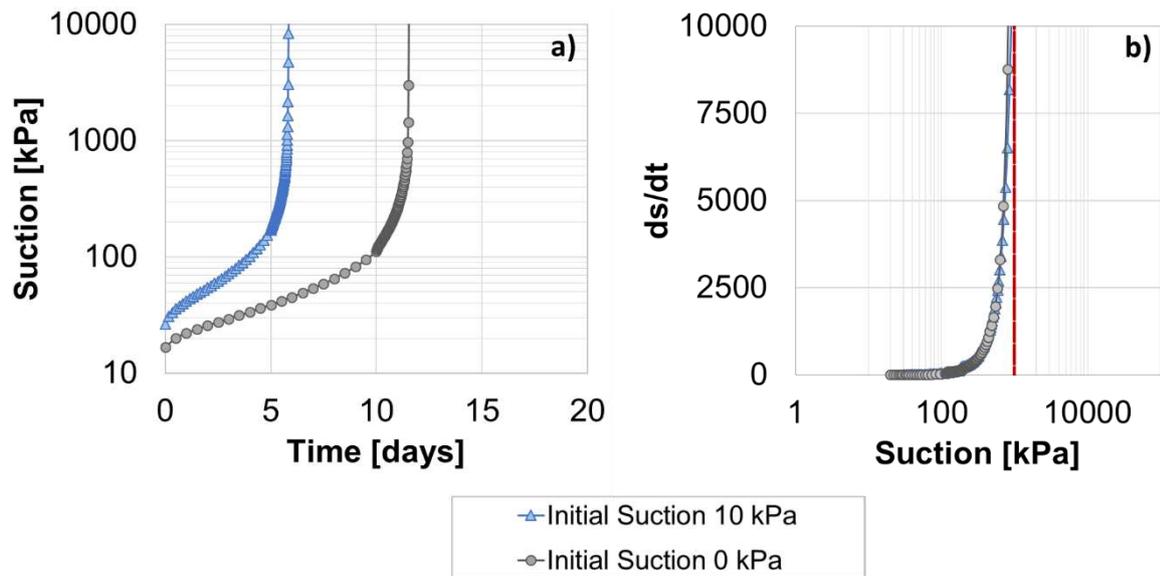


Figure 18. Identification of the limit suction value.

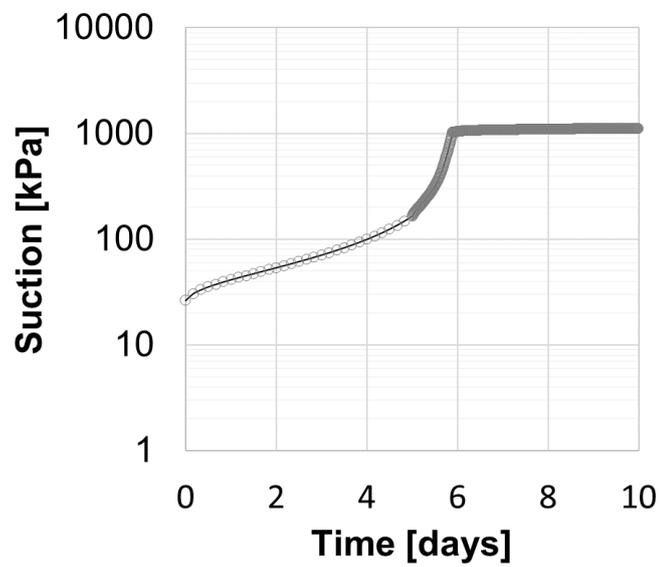


Figure 19. Identification of the value of suction at which the Actual Evapotranspiration goes to zero.

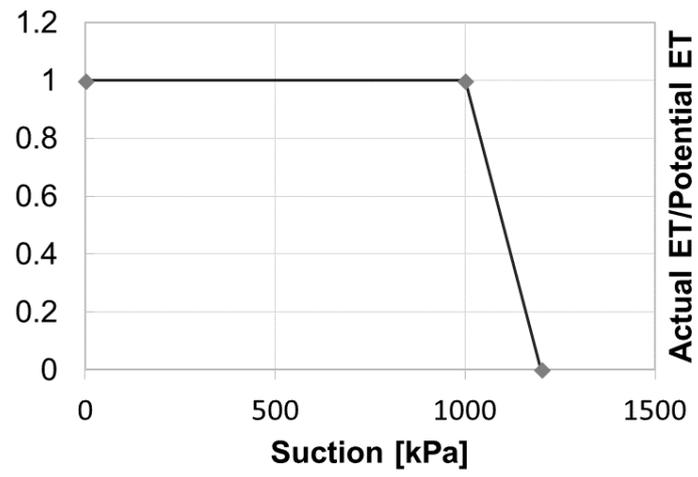


Figure 20. Reduction function calibrated on the Gagnano soil profile.

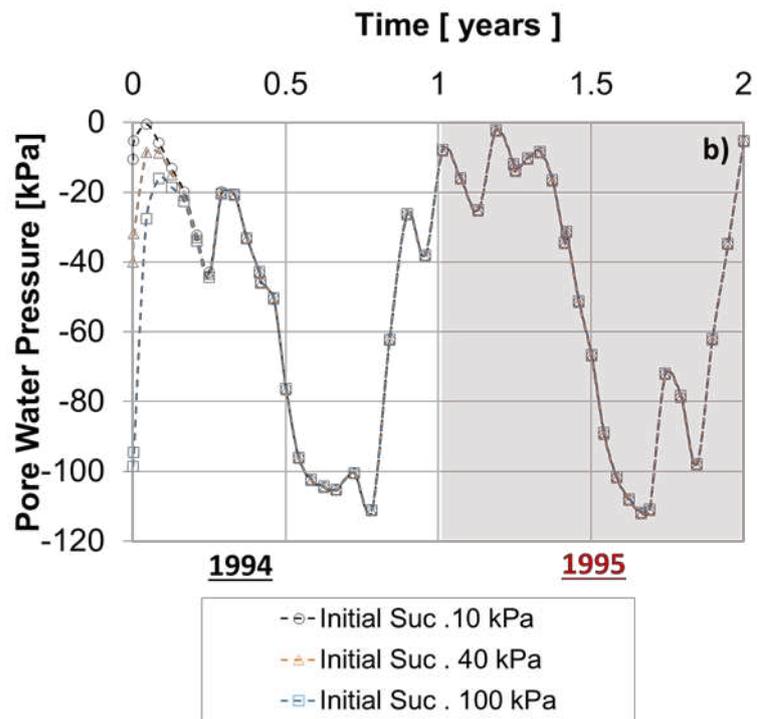
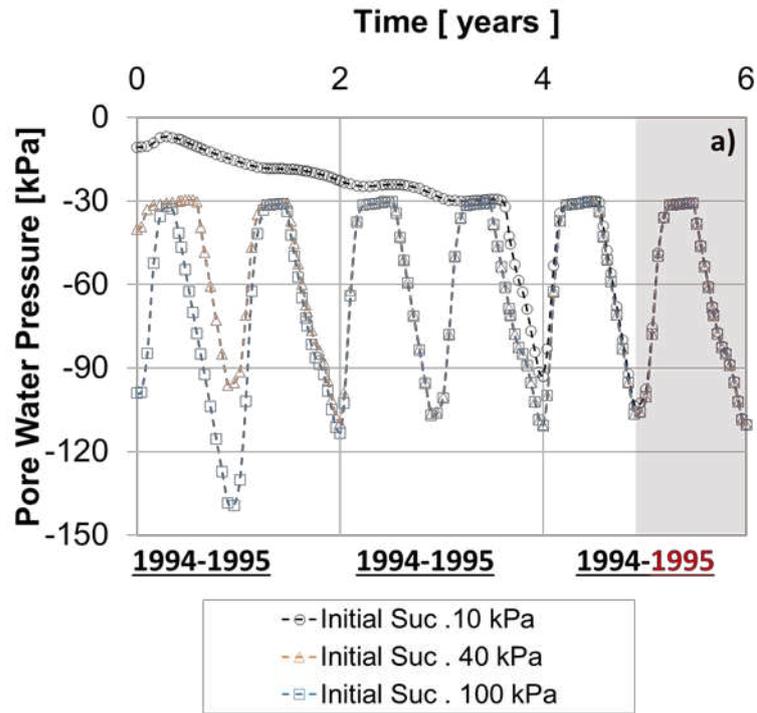
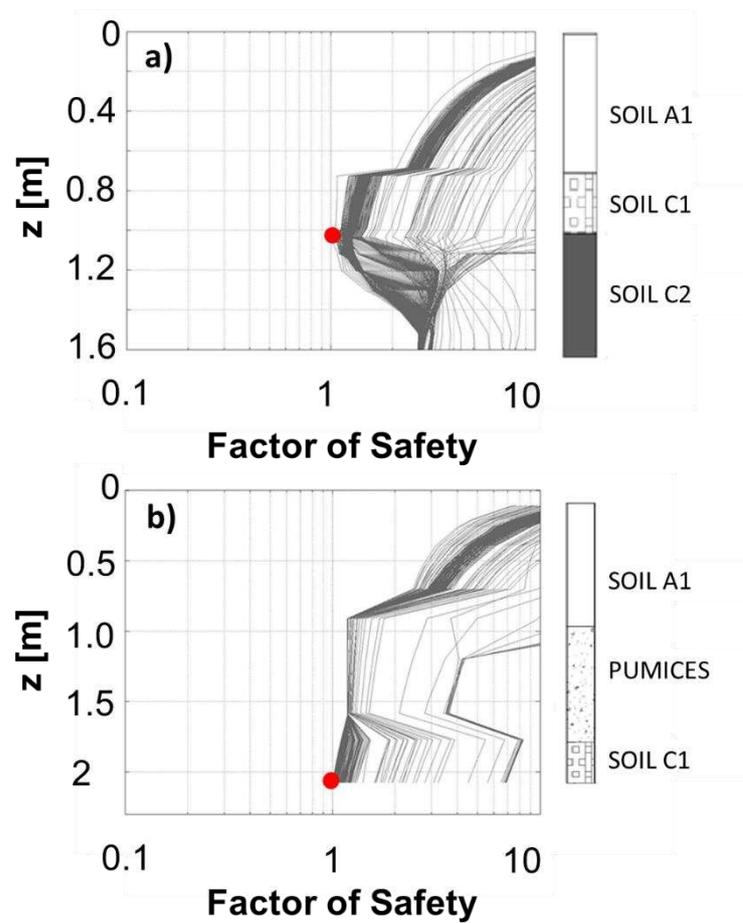


Figure 21. Cancellation of the initial condition at the bedrock for a) Gragnano's model and b) Corbara's model.



**Figure 22. Evolution of the Factor of safety profile from January 1996 to the 10<sup>th</sup> of January 1997 when the Landslide events occurred in Gagnano(a) and Corbara(b).**

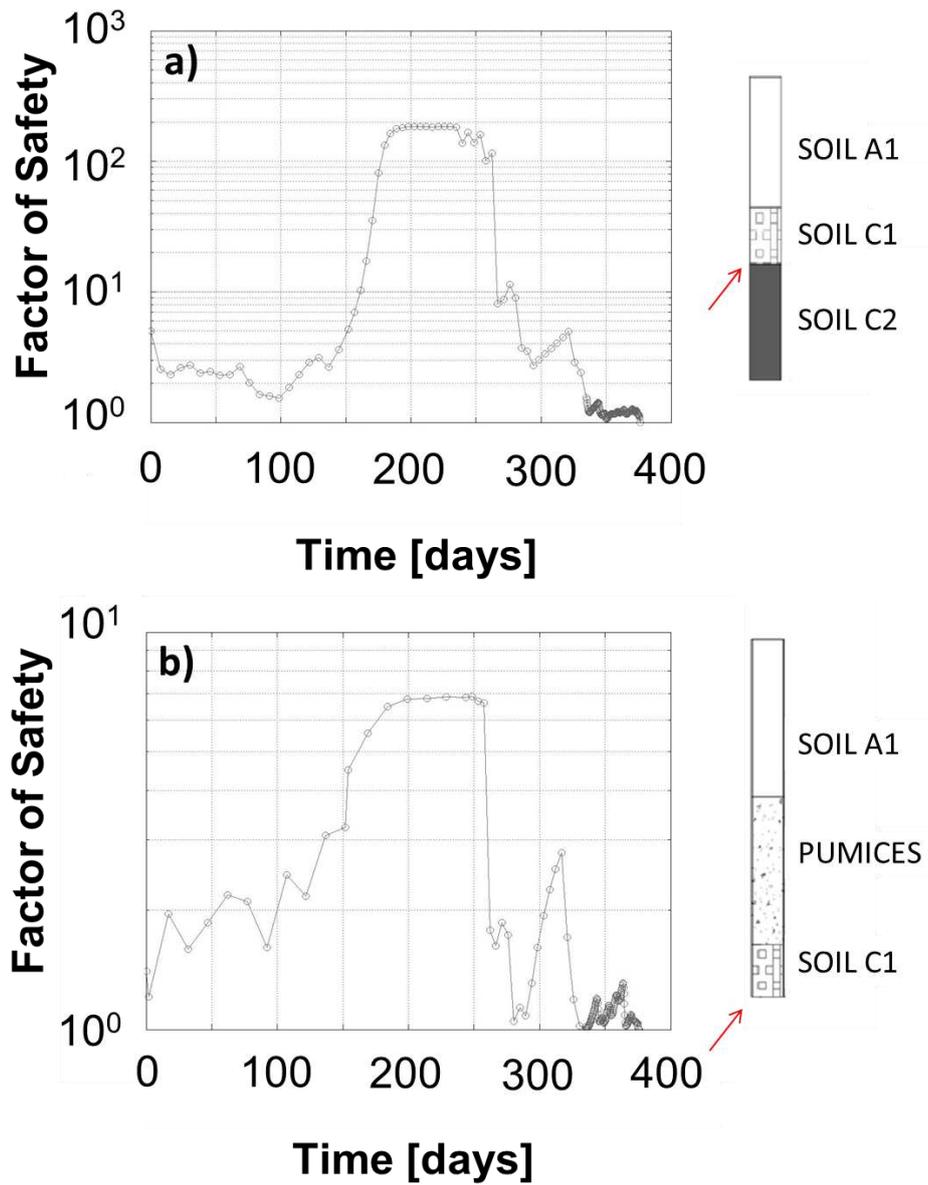
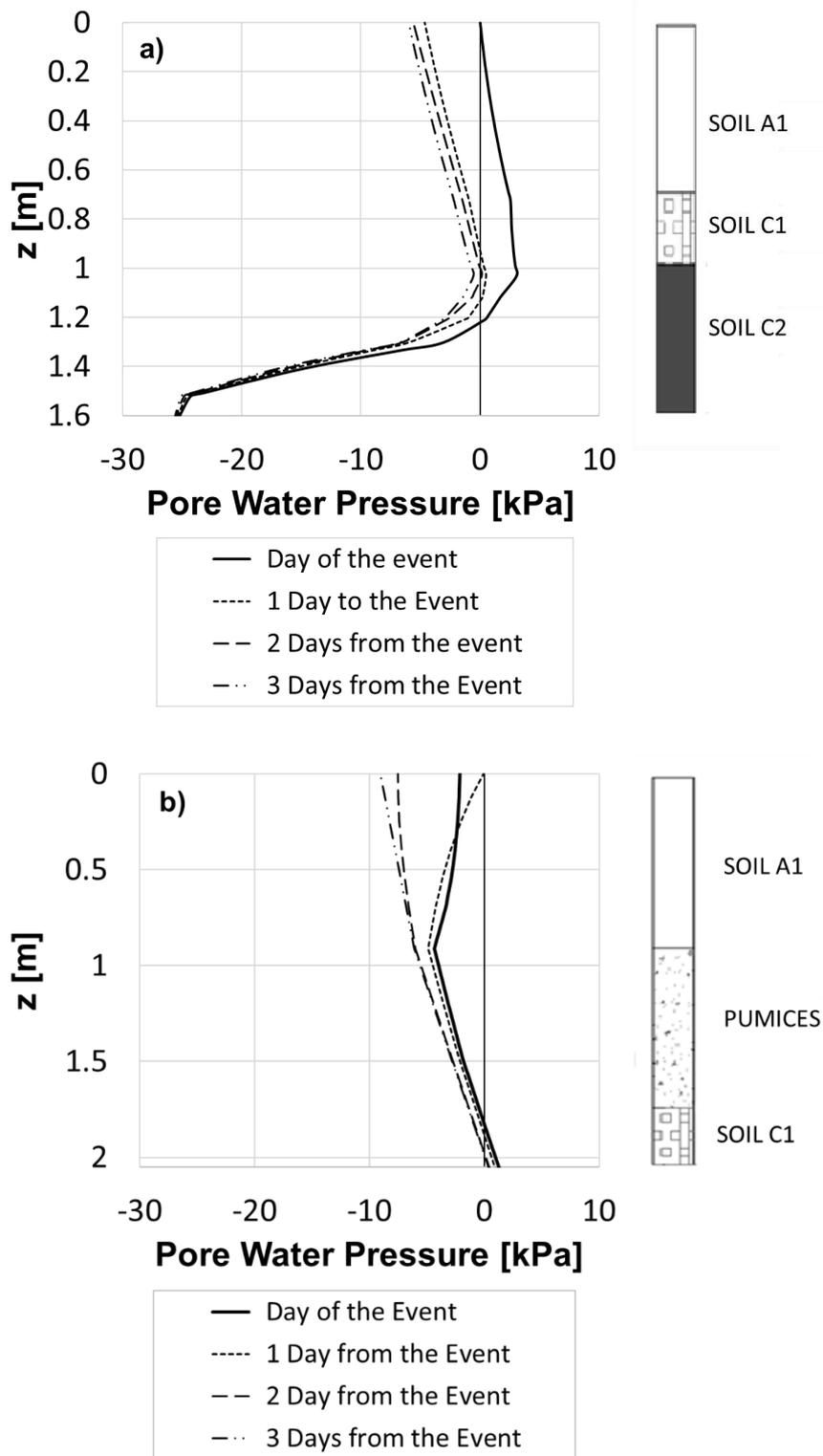


Figure 23 Evolution of the minimum Factor of safety profile from January 1996 to the 10<sup>th</sup> of January 1997 when the Landslide events occurred in Gragnano (a) and Corbara (b).



**Figure 24. Pore water pressure profile at the time of the failure in Gragnano (a) and Corbara (b).**