The large Ancona landslide studies revisited including stochastical spatial variability of mechanical parameters

SCIARRA N.[1], PASCULLI A.[2] & CALISTA M.[3]

[1] *Engineering, University of Chieti, Chieti, Italy (e-mail: nsciarra@unich.it)*
[2] *Engineering, University of Chieti, Chieti, Italy (e-mail: a.pasculli@unich.it)*
[3] *Geologist, University of Chieti, Chieti, Italy (e-mail:* m.calista@unich.it*)*

Abstract: The great landslide that occurred in Ancona in 1982 caused damage to human livelihoods, buildings, railways, and roads. Many studies have been already carried out from different perspectives. The most common approaches in this field have used deterministic methods in relation to mechanical parameters. However, it is well known that local heterogeneities may have a non vanishing influence on landslides occurrence. Thus, in this paper, we explored the effects of an assumed stochastical spatial variability of the principal parameters, based on experimental measures, on the spatial hazard distribution of selected areas around Ancona, by means of a Probabilistic Approach. Then several trials have been carried out, applying the three dimensional code FLAC-3D, each time considering a different set of some selected mechanical parameters (i.e. density, friction angle, Young Modulus, cohesion), determined by random number generation routines among the "ensemble" of all the possible "realizations" of the selected statistic (Gaussian) to which the set of the numerical values of each parameters have been supposed to belong. Furthermore a "random variability algorithm", developed by some of the Authors, has been implemented. In particular kinematic evolutions of weakness, characterizing the territory of Ancona, determined by stochastical approaches, have been compared with numerical results carried out by deterministic modelling.

Résumé: Le grand glissement de terrain s'est produit à Ancona en 1982 a endommagé beaucoup des vies humaines, aux bâtiments, aux chemins de fer, aux routes. Beaucoup d'études ont été déjà effectuées par différents points de vue. Les approches les plus communes dans ce domaine considérent les champs déterministes in relation des paramètres mécaniques. Comme chacun sait, les heterogeneities locaux peuvent avoir une influence non insignifiant sur l'occurrence d'éboulements. Donc, en cet article, nous avons exploré les effets d'inclure une variabilité spatiale stochastique devinée des principaux paramètres, basée sur des mesures expérimentales, sur la distribution spatiale de risque des secteurs choisis autour d'Ancona, également au moyen d'une approche probabiliste déjà proposée par les auteurs. Donc, pour acquérir majeur connaissance dans cette problématique, l'analyse de sensibilité, y compris la variabilité spatiale des paramètres physique-mécaniques, liée à une structure géologique réelle, ont été effectuées avec application du code tridimensionnel Flac-3D. Alors plusieurs cycles de calcule ont été effectués, considérant chaque fois des valeurs différentes de quelques paramètres mécaniques (densité, angle de friction, module de Young, cohésion), déterminé par la génération de nombres random, par le programme FISH, parmi l'"ensemble" de toutes les possibles "réalisations" des statistique choisie (Gaussiennes) auquel l'ensemble des valeurs numériques de chaque paramètre ils ont été supposés appartenir. En outre "un algorithme aléatoire de variabilité", développé par certains des Auteurs, ont été mis en application. En particulier des évolutions cinématiques, caractérisant le territoire d'Ancona, déterminé par des approches stochastiques, ont été comparées aux résultats numériques effectués par une usuelle analyse déterministe

Keywords: 3D models, landslides, mechanical properties, safety

INTRODUCTION

The large landslide of Ancona started in the evening of 13th December 1982, at about 10.45 p.m., on the north-facing slope of the Montagnolo, moving from about 170 metres a.s.l. (above sea level) down to the sea. The slope portion affected by mass movement extended over about 3.4 km^2 and along the shore it is about 1.7 km wide. The deformation phase lasted only a few hours. Many buildings were damaged beyond repair and some completely collapsed. Lines of communications such as the Flaminia Road and the railway were interrupted (Fig. 1), lifted and moved towards the sea. This impressive landslide has an ancient origin; after its early activation the phenomenon has moved sporadically, coincident with significant rainfall events or earthquakes.

The study of landslides implies first of all a suitable characterization of the system from different perspectives. One concerns a reasonable reconstruction of local and global geometry of the involved geological structures of the system. Another regards the problem of how to handle, in a satisfactory way, the spatial variability of important parameters related to the selected constitutive models. Each modelling approach requires the selection of the most important features which have greatest influence on the computer model. With as accurate as possible reconstruction of the system, landslide modelling has been performed applying a three dimensional computer code: FLAC-3D. The soil was simulated by the code default *elastic-perfectly-plastic* model with failure being described by a composite *Mohr-Coulomb criterion* with a tension cut-off. The starting point of the study we have discussed in this paper was to assume the location of the slide surface from experimental evidence. Then we analyzed the behaviour of the landslide body. We introduced two kinds of heterogeneities: the first one at small scale, the result of a random (Gaussian) variability of the mechanical parameters; and the other one including the small scale around larger scale heterogeneity, assumed a linear variation of the parameters with the depth. The applied methodology has been already proposed and discussed by Pasculli & Sciarra ((2002a & b) and Pasculli et al. (2006).

We carried out a first simulation supposing averaged parameters values, spatially constant. Then we considered, for each material, the smaller scale variability alone, through a random Gaussian realization of the mechanical properties without any deterministic trend. The simulation was performed considering first the variability through the slide surface alone and then including the landslide body as well. In the fourth and fifth simulations, we also had to analyze the combined effect of the two selected kind of variability at different spatial scales, considering, as in the two previous cases, first the inclusion of the spatially variability only through the slide surface and, after, through the body as well.

Figure 1. Railway (a) and Flaminia Road (b) interrupted by the landslide.

GEOLOGICAL FRAMEWORK

Plio-Pleistocene sediments crop out in the study area. The Middle Pliocene is represented by gray-blue bedded marl with sandy and silty interbedding. These rocks are unconformably overlaid by gray-bluish silt and sandy clays which, in the upper part, contain levels of sands and sandstones, and lenses of coquinic panchina; the age of these sequences is Pleistocene. The Pleistocene sediments were uplifted by about 250 m in line with the top of Montagnolo hill. They appear to be strongly lowered towards the sea, north of the Posatora-Grottine alignment, along which a normal fault was observed. Plio-Pleistocene units are intensely jointed and eluvial-colluvial deposits, at places tens of metres thick, nearly everywhere overlie them. The main tectonic features of the area fit the framework of the northern Apennine range; folds with axes trending NW-SE, faults striking NW-SE and NE-SW (Fig. 2). From seismic data (Crescenti et al., 1977), it can be inferred that some epicentres are roughly aligned along faults striking NE-SW in the vicinity of the landslide area.

From a geomorphologic point of view the Montagnolo hill shows a characteristic landslide morphology with scarps, steps, undrained depressions (trenches) and a reverse slope. Two flat-floored parallel trenches extending at elevations of about 140 m and 80 m (Posatora trench), respectively, constitute the most striking geomorphologic elements of the slope. They are graben-like features, being bounded by tensile fractures with vertical displacement. (Fig. 3). The upper trench is circa 700 m long, while the lower one is 1200 m long from Posatora to Grottine. The dimensions of the involved area and the fact that deformations occurred at the same time suggested that the phenomenon was a very deep one (Fig. 3). Geognostic and geophysical surveys confirmed this hypothesis (AA.VV, 1987). Therefore, on the basis of historical data (De Bosis in 1859 and Segrè in 1919 described the same event that occurred in November 1858), we can conclude that the large Ancona landslide of December 1982 is a very ancient, deep and complex phenomenon. It is ancient (more than 5000 years B.P.) based on historical records and the morphological evidence. It is deep and complex (see Carrara et al., 1985) because near the deep rotational-translational movement that affected the Pliocene substratum, superficial landslides are also present with flow or sliding forms.

FLAC-3D MODEL RECONSTRUCTION AND STABILITY ANALYSES

A numerical grid has been built up by more than 132,602 tetrahedrons whose largest dimension was of 20 metres at the surface. The soil was simulated with the *elastic-perfectly-plastic* model with failure being described by a composite *Mohr-Coulomb criterion* with a *tension cut-off*, implemented by default in FLAC-3D (Itasca Consulting Group, 2000). Then, in order to make some further quantitative evaluations about the hazard of local instabilities relative to the geological system, the criteria we adopted to analyze was how far the local stress state was from the failure region in the principal stress planes (σ_1, σ_3). Since the following *Mohr-Coulomb* with *tensile cut-off* failure criteria has been assumed (with the evidence of the symbols):

$$f^s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi}; \qquad f^t = \sigma_3 - \sigma^t$$
$$N_\varphi = [1 + sin(\varphi)]/[1 - sin(\varphi)]; \quad \sigma^t_{max} = c/tan(\varphi) \tag{1}$$

[For definitions of the terms not included in the text refer to Figure 4]

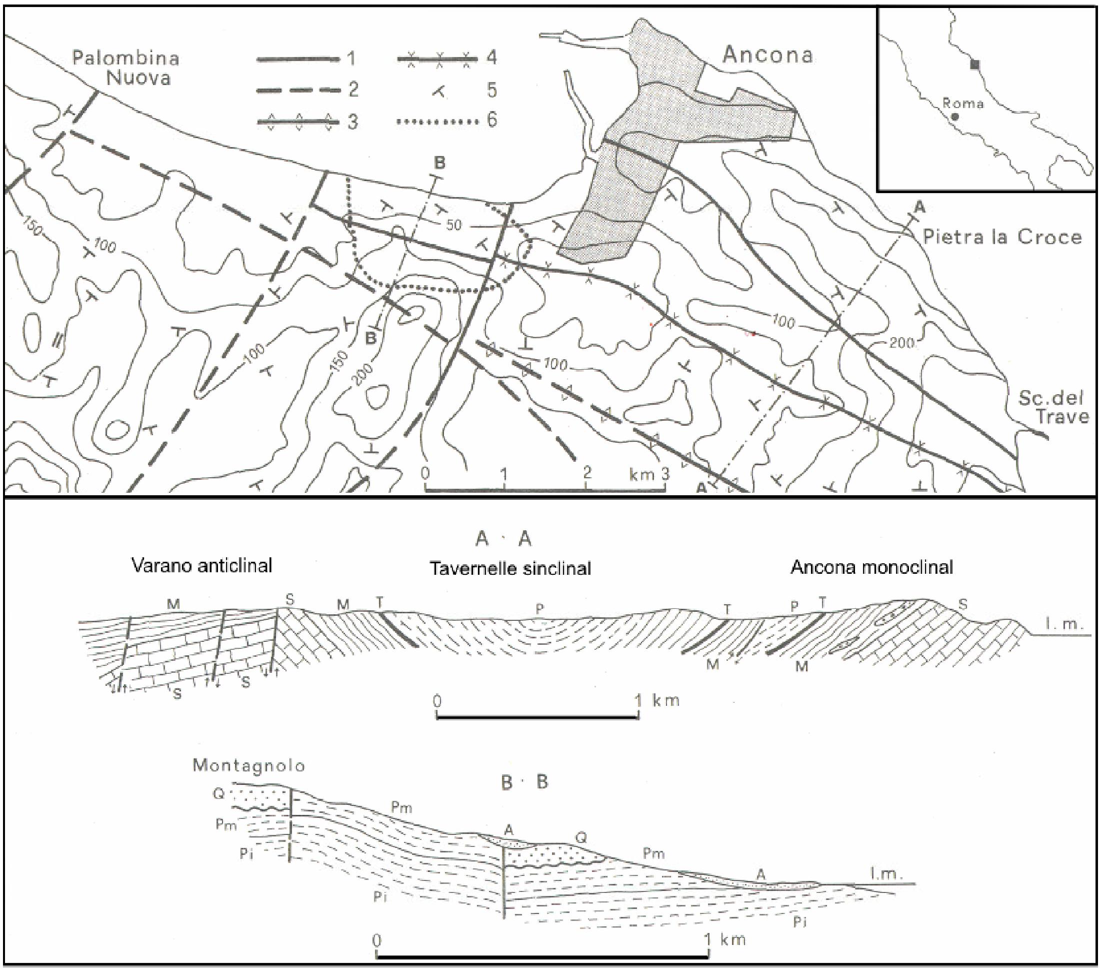

Figure 2. Main tectonic features of the area: 1) faults; 2) probable faults; 3) anticlinal axes; 4) synclinal axes; 5) dip; 6) landslide boundary; S (Schlier formation - Middle Miocene); M, T (clays, marls, sandstones – Upper Miocene); P (marly sandy clays – Lower Pliocene Pi, Middle Pliocene Pm); Q (Pleistocene); A (cover deposits).

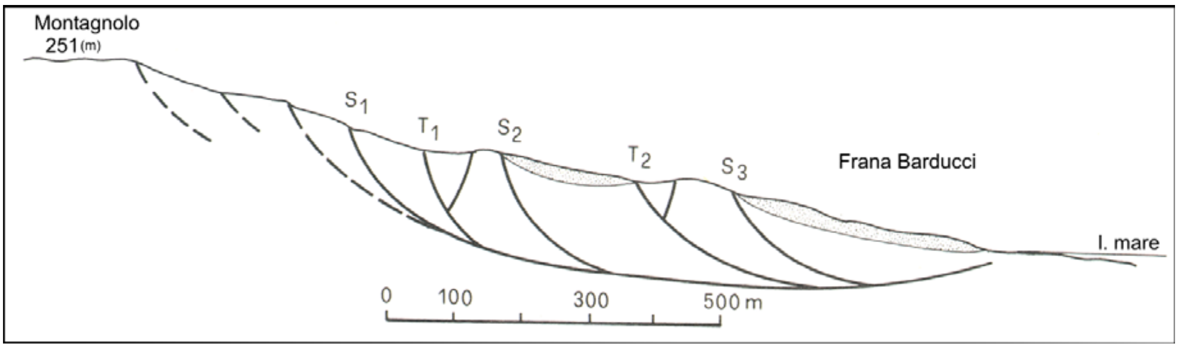

Figure 3. Schematic section from the Montagnolo hill to the sea. We can recognize the main and secondary scarps (S1, S2 and S3) and the trenches (T1 and T2).

The simplest indicative parameter which may be introduced for this purpose is just the distance d_i of the point P from the Mohr Coulomb line on the stress plane (see Fig.4):

$$d_i = \frac{\left|\sigma_{1i} - \sigma_{3i} N_{\varphi i} + 2c_i\sqrt{N_{\varphi i}}\right|}{\sqrt{1 + N_{\varphi i}^2}} \tag{2}$$

We called d_i the *strength failure indicator (SFI)*, relative to the *i-th* spatial mesh. In this case the surface of the already occurred landslides is modelled supposing very degraded, almost vanishing, shear modulus, while the other parameters are simulated by the discussed methodologies. In order to apply a *micro zoning landslides* concept, we have divided the system into four sectors as displayed in Fig. 5 in which the numerical grid, adopted in all the simulations, has been reported.

MODELING WITH SPATIALLY CONSTANT PARAMETERS

For the first numerical experiment, which we have called case A, the arithmetic averaged values of the mechanical parameters (Table 1), were assumed to be spatially constant through the zones characterized by a single equivalent material. Fig. 6 shows the plot of the failed zones ($d_i=0$) provided by the numerical simulation. It may be clearly observed that the region with an elliptical label does not show evidence of any failed soil materials, based on the experimental evidence.

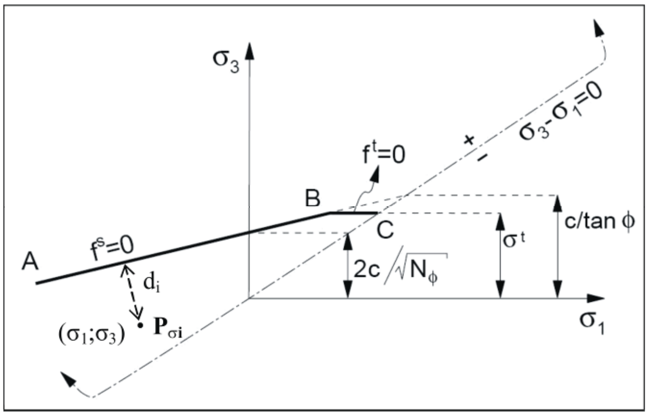

Figure 4. Principal stress plane with failure criteria associated to the *i-th* spatial mesh

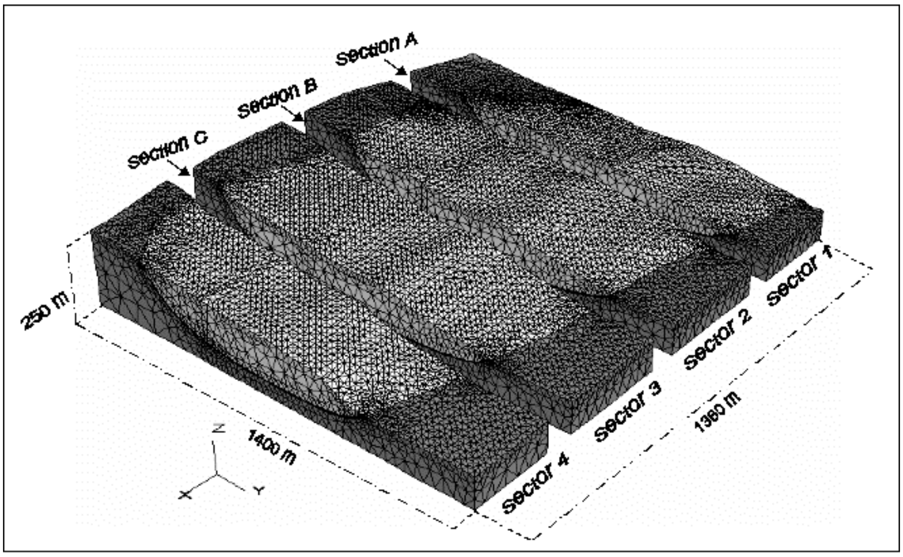

Figure 5. Exploded map of the landslide body under consideration

Table 1 Mechanical parameters and some selected range variability from laboratory measures

Parameters	Cover deposits	Clays	Remolded clays
γ (unit volume weigh) – (kNm^{-3})	18.5 – 19.8	21.0	19.0
c’ (cohesion) – (kPa)	1.0 – 10.0	30.0	0.0
φ’ (friction angle – (°)	18 – 21	25	13 - 18
bulk modulus – (MPa)	0.43e6 – 4.33e6	6.0e6	6.0e5
shear modulus – (Pa)	0.2e6 – 2.0e6	4.0e6	0.4e3 – 4.0e3

PROBABILISTIC APPROACH

In a previous paper (Pasculli et al., 2006) a *Probabilistic Approach* has been proposed. In order to make a comparison with the results so far analyzed, in the following a brief synthesis of the adopted method is reported. The usual procedure in numerical modelling implies the assignment of averaged values of mechanical parameters to each lithotype layer. In a non-linear condition it is debatable if this kind of approach may or may not provide conservative results with respect to actual values (Kaggwa, 2000). Thus in the literature, in order to include the inevitable spatial variability, several methodologies have been discussed, but usually they are based on the following equation:

$$Phys(P) = \mu(P) + \delta \tag{3}$$

where $Phys(P)$ is the random parameter at the point *P*, $\mu(P)$ is the averaged value of the selected parameter and δ is the random perturbation usually assumed as a *Standard Gaussian*. In the proposed method, however, we adopted a simplified 3D version of a 2D approach, particularly suitable for granular soils (Pasculli & Sciarra 2002a, b) and implemented in FLAC-3D through the FISH program. In this model the selected parameters $Phys(P)$ are assumed to be the result of two physical causes: the first one is supposed to be due to the random formation of the granular deposit layer, while the second one is supposed to be due to a stochastic force, around a deterministic trend.

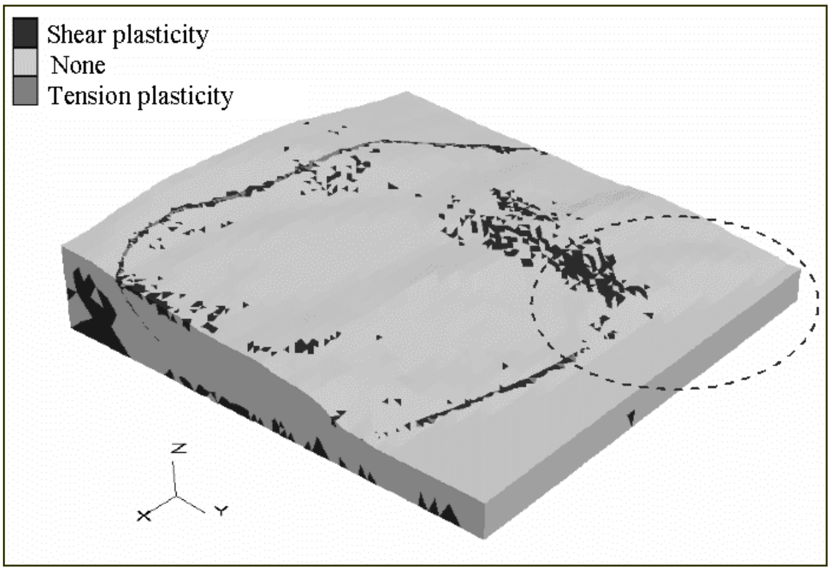

Figure 6. Case A: spatially constant parameter simulation; plot of failed soil material

The second term, which we call *stochastic-deterministic constraint (SDC)*, is supposed to include all the mechanical influence of the system on the soil element around the point *P*. The difference with the more common approach (Equation 3) is that the stochastic character of the phenomena is not imposed by a simple mathematical term (δ), but it is, in some way, justified by a physical point of view. Thus the following equation has been employed:

$$Phys(P) = Phys\_r(P) + [\mu(P) - Phys\_r(P)] \cdot [mean + \sigma \cdot G\_norm] \cdot e^{-[f(P)/s]^2} \tag{4}$$

where *Phys(P)* was again the random parameter (Young Modulus, Friction angle, cohesion, bulk unit weight and so on) at the point *P*; *Phys_r(P)* was the value due to the random formation of the selected soil layers; $\mu(P)$ was the deterministic trend of the *SDC*, while the term [$mean+\sigma \cdot G\_norm$] was a non-dimensional number related to the random factor of the exerted *SDC*, in which "mean" was the average term, σ the standard deviation $\sigma_x = \sqrt{\left(\sum_{i=1}^{N}(x_{ki} - x_m)^2\right) \Big/ N}$ and *G_norm* the *Standard Gaussian distribution*. The last factor $e^{-[f(P)/s]^2}$ has been introduced to include weakness and perturbations (just like fractures, for example), localized along curves or geometrical zones described by the *f(P)/s* function. For all the numerical experiments discussed in this paper $e^{-[f(P)/s]^2} \equiv 1$ has been assumed. The related *Standard Gaussian distribution* has been provided by the Box & Muller (1958) algorithm:

$$G\_norm = \sqrt{[-2ln(y\_ran1)]} \cdot cos(2\pi \cdot y\_ran2) \tag{5}$$

where *y_ran1* and *y_ran2* were two non-correlated (pseudo) random variables uniformly distributed in the interval (0,1) and provided directly by the FISH function URAND.

The bulk unit weight of the materials has been selected as the random variable, while the other parameters have been employed as a linear function of it, in such a way as to save their variability through the numerical range, provided by laboratory tests and as reported in Table 1. For all the simulations, Poisson coefficient $\nu=0.3$ has been assumed. For the 'only small scale variability', the bulk unit weight has been supposed to be a Gaussian variable independent of depth. Thus from equation (9), setting *mean=0* and $\sigma=0$, it followed: *Phys(P)=Phys_r(P)*.

For all the analyses discussed in the following, we have supposed, for simplicity and for the aim of this paper, that the numerical variability of a selected parameter: $x_{min} \le x_k \le x_{max}$, where x_{min} and x_{max} have been provided by the minimum and maximum laboratory measured values reported in Table 1, and was related totally to the spatial heterogeneities. Further, considering x_k as a stochastic variable, it is well known that, for the *Chebyshev inequality*, about 93% of the numerical values of x_k lies in the range: $x_{mean} - 4\sigma_x \le x_k \le x_{mean} + 4\sigma_x$ independent of the probability distribution function. Thus, in order to satisfy the double constraints $x_{min} \equiv x_{mean} - 4\sigma_x$ and $x_{max} \equiv x_{mean} + 4\sigma_x$, where $x_{mean} = (x_{min} + x_{max})/2$, we assumed:

$$\sigma_x = \frac{x_{max} - x_{mean}}{4} \tag{6}$$

which satisfies directly the upper bound, while for the lower bound, introducing the relationship (4) directly into the $x_{min} \equiv x_{mean} - 4\sigma_x$, it follows the requested identity: $x_{min} \equiv x_{mean} - 4\frac{(x_{max} - x_{mean})}{4} \equiv 2x_{mean} - x_{max} \equiv x_{min}$.

Random values eventually outside of the range have been assumed to be equal to the mean. Then we employed the following relation: $\gamma = \gamma_{mean} + (\sigma_\gamma \cdot G\_norm)$ for the simulations for which only small scale heterogeneities have been supposed and on which the other parameters were linked through the linear expression as discussed below.

In the case for which the values of the material parameters have been supposed to change linearly through the depth, from Eq. 4 and after the aforementioned discussion, the following expression for the selected parameter has been employed: $\gamma = \gamma\_r + [\mu - \gamma\_r] \cdot [1 + 0.125 \cdot G\_norm2]$, where: $\gamma\_r = \gamma_{mean} + (\sigma_\gamma \cdot G\_norm1)$ was the Gaussian random value of the density around γ_{mean} with the standard deviation σ_γ, *G_norm1* and *G_norm2* were two *Standard Gaussian* variables extracted by two different, subsequent calls to the FISH (pseudo) random routine URAND.

The term μ was the deterministic trend of the effects of the total force exerted on the soil element, which, in this case, was supposed to be due to the lithostatic loading and assumed to be equal to the following equation:

$$\gamma(P) = \frac{(\gamma_{max} - \gamma_{min})}{[h_{max} - h_{min}]} z(x,y) + \gamma_{min} \tag{7}$$

The variation law of the other parameters has been supposed to follow linear trends:

$$x = (x_{max} - x_{min}) \frac{[\gamma_c(x,y) - \gamma_{min}]}{(\gamma_{max} - \gamma_{min})} + x_{min} \tag{8}$$

In the proposed approach, the mechanical parameters correlation between different soil points and their scale fluctuations (Fenton & Vanmarcke, 1990; Vanmarke, 1977) have not been included. This assumption is partially justified by the large scale of the whole system and by the necessity to carry out as fast (in terms of computer time) as possible simulations. After having stated the basis of the proposed method, 20 runs have been carried out for each type of simulation, considering each time, in an automatic way, a different value of the selected parameters, extracted randomly among the "ensemble" of all the possible "realizations" of the aforementioned statistic, to which the set of the numerical values of the considered parameters has been supposed to belong.

Modelling with small scale variability

For the second numerical experiment, which we have called case B, the parameters have been assumed to vary randomly as in the previous discussion. Fig. 7 shows two plots: in the left a realization (among the 20 made) related to random parameters only through the landslides layer; in the right a realization (among another 20 different simulations) related to random parameters through both the landslides layer and the landslides body. For these simulations, only small scale variability has been included. It can be observed that a better numerical prevision of the failed soil distribution, with respect to the actual phenomena, has been achieved. Not all the realizations, just a few however, have shown this good qualitative match with the actual situation.

Modelling with both small and large scale variability

For the third numerical experiment, which we have called case C, the parameters have been assumed to vary randomly around a linear deterministic trend on the depth as discussed above. Fig. 8 shows two plots again: in the left a realization (among the 20 made) related to spatial variability only through the landslides layer; in the right a realization (among another 20 different simulations) related to spatial variability through both the landslides layer and the landslides body. In this case all the realizations have displayed a good qualitative prevision, indicating, for this geological system, the usefulness of the approach. Furthermore, in Figures 9 and 10, displacements of the whole system and for the three sections indicated in Fig. 5 have been reported.

RESULTS ANALYSES, STATISTICAL CONSIDERATIONS AND COMPARISON

To analyze the risk of instability at an intermediate scale, we divided the selected geological system into four sectors, as reported in Fig. 5, in an exploded view. Then, in the framework of a numerical "probabilistic micro zoning" procedure related to instability risk, we introduced two simple numerical indicators calculated for each run that are related to each spatial sector in which we have divided the selected system. The first one was a plasticity ratio: $DI_{ik} = V_{ik} / V_{itot}$ where V_{ik} was the soil mesh volume of the sector *i-th* in a plasticity state, obtained in the *k-th* running, while V_{itot} was the total volume of the *i-th* sector layer.

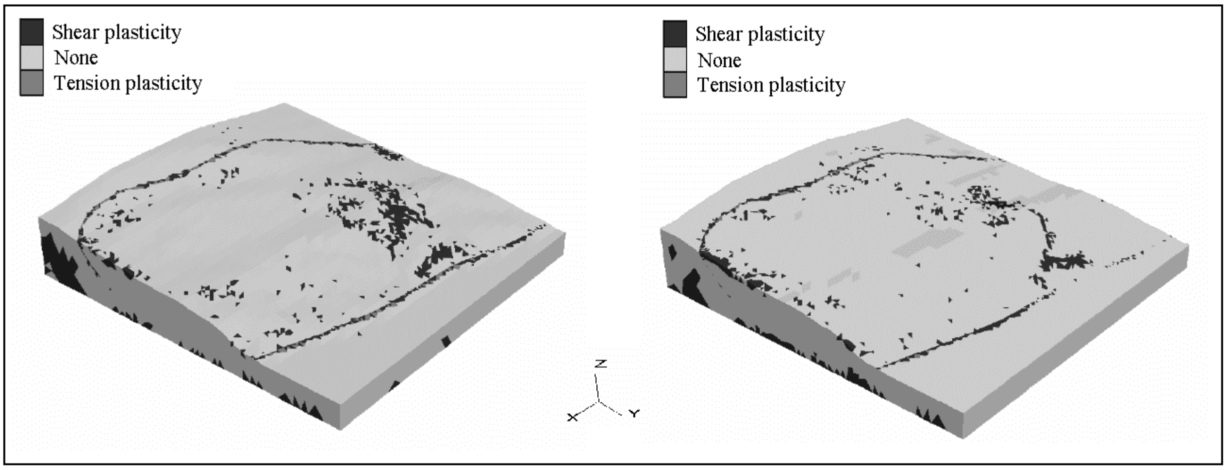

Figure 7. Case B. Left: small scale random spatially parameter realization only through landslides layer; Right random parameters through both the landslides layer and the landslides body.

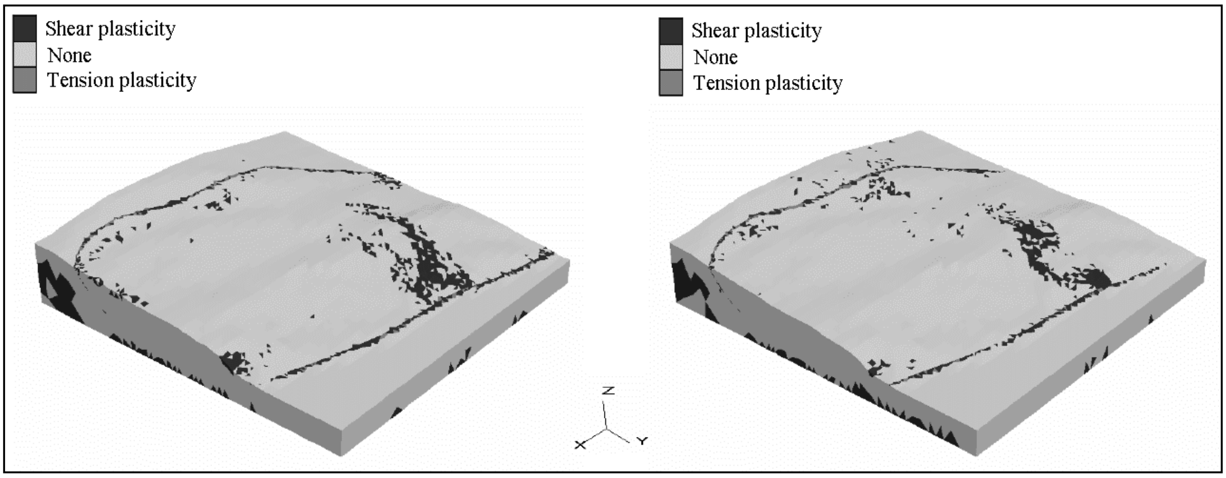

Figure 8. Case C. Left: random spatially parameter realization with both the heterogeneities, only through landslides layer; Right: random parameters through both the landslides layer and the landslides body

The second one, calculated again for each sector, was an averaged strength failure indicator, weighted by means of the "importance" ratio of the volume V_j of the *j-th* mesh over the total volume V_{itot} of the *i-th* sector:

$\mu_{di} = \frac{1}{N_i} \sum_{j=1}^{N_i} \left[d_j \frac{V_j}{V_{itot}} \right]$ where N_i was the number of the meshes in the *i-th* sector.

The first indicator was related to the calculated mobilized mass for each sector and for each run, thus indicating how much the soil material inside the selected sector has been damaged. So we called it the *numerical degrade indicator (DI)*. The second one specified, numerically, how far the stress state of the soil material was from failure conditions. We called it: *numerical hazard stress state indicator (HSSI)*. In Figs. 11 and 12 we reported the occurrence number of the analyses for which a specific ratio value of the plastic soil mass, over the total mass in the selected sector (*DI* value) has been provided by the 20 simulations. Thus it would be straightforward, by normalizing the ordinate to the total simulation number, to obtain an estimation of the *Probability of the failed soil mass amount* in each sector.

The calculated percentage of the soil in a plastic state, ranged from 0.15% up to 19%. It is interesting to note that the effects of the selected random spatial variability have been more important, in particular for sectors 2, while the "probability distributions" related to the other sectors have not been so spread out along the whole range, thus these sectors are less sensitive to the inclusion of the variability of the mechanical parameters in the modelling. In the same figure we report the calculated values for A case, with constant parameters.

In addition we analyzed another important parameter: the numerical *stress state hazard indicator* (see Figs. 13 and 14). In this case, the selected parameter μ_{di} has been calculated for each sector and for all the runs. Due to its large numerical variability (several orders of magnitude), we considered its natural logarithm and then we plotted the related *occurrence number*. The effects of the selected random spatial variability have been more important for sector 2, while the "probability distributions of the failed soil percentage" related to the other sectors have not been so spread out along the whole range. Thus these sectors have been less sensitive to the inclusion of the variability of the mechanical parameters in the modelling. It is interesting to note that the values of the natural logarithm of the *stress state hazard indicator* predicted by the *Probabilistic Approach* with both kinds of variability are shifted toward the lower values than those predicted by constant parameters, indicating an higher *stress state hazard* than that obtained by an usual approach.

CONCLUSIONS

In this paper the Ancona landslide has been studied firstly by a normal method, considering averaged values of soil parameters, and applying the three dimensional commercial computer code FLAC-3D. The results have been compared with the response of a *Probabilistic Approach*. For all the analyses, the soil has been simulated by the FLAC-3D default *elastic-perfectly-plastic* model with failure being described by a composite *Mohr-Coulomb criterion* with a tension cut-off. The starting point of the analyses has been the imposition of the known landslides surface by lowering the related shear modulus.

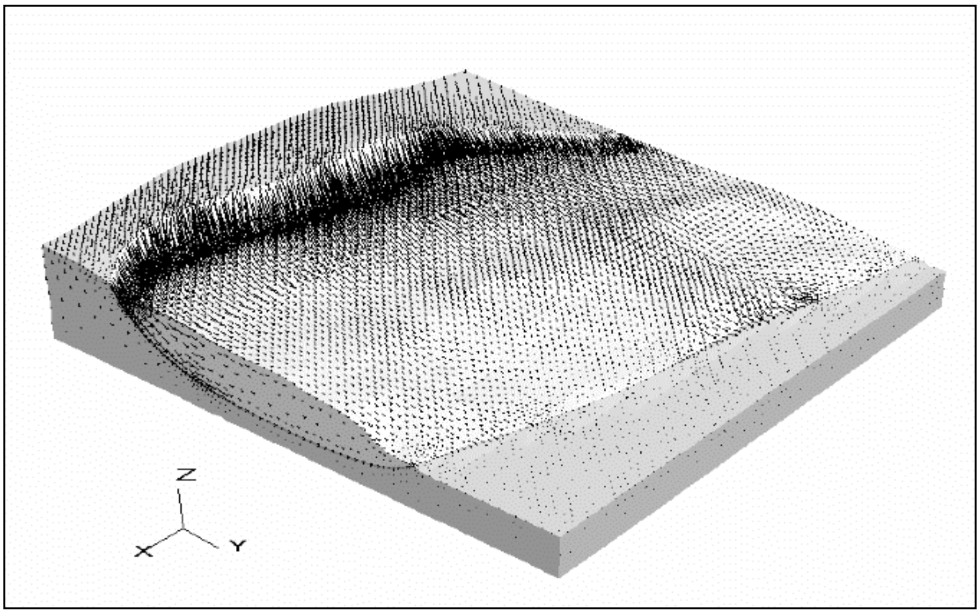

Figure 9. Global displacements view of the case displayed in fig. 8

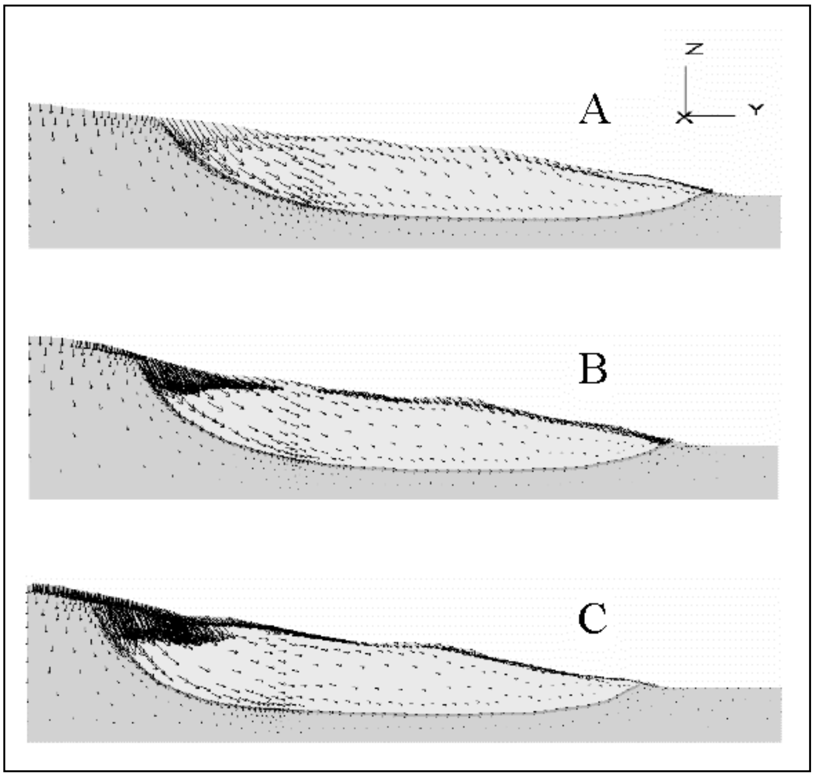

Figure 10. Displacement of the three selected sections A, B, C (see fig. 5)

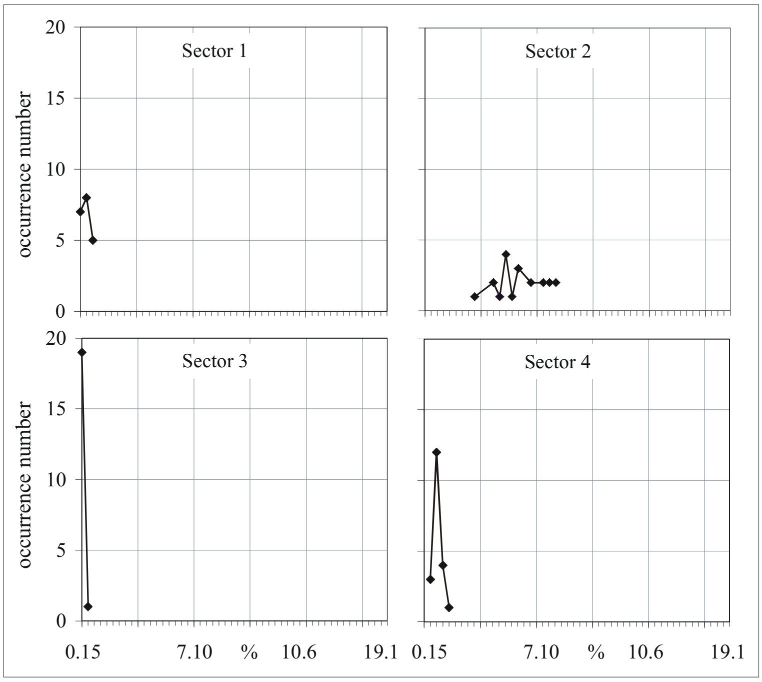

Figure 11. Distribution of the failed soil material percentage for each sector related to the case in which only small scale variability is assumed in both landslides body and landslides surface.

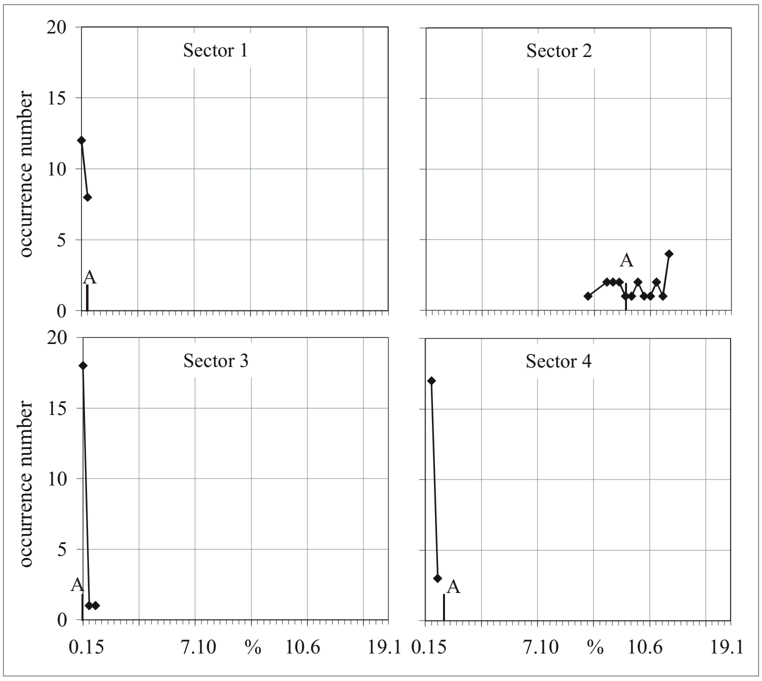

Figure 12. Distribution of the failed soil material percentage for each sector related to the case in which both small and large scale variability are assumed in both landslides body and landslides surface.

The simulations have been carried out assuming, for each case, different values of the selected mechanical parameters, whose numerical ranges have been supplied by laboratory tests related to each materials, in order to take into consideration large and small heterogeneities.

In the aforementioned *Probabilistic Approach*, a modelling based on a random number generation of numerical values of the selected parameters, has been applied through 20 runs of the same model, for each kind of the selected variability typology, but each time with a different spatial realization of the assumed Gaussian statistic.

Further, in order to introduce a *micro zoning* procedure, we discussed other statistical parameters, namely: the *degrade indicator (DI)* related to how much the soil material inside the selected sector has been damaged; and the *stress state hazard indicator (SSHI)* which specifies how far the stress state of the soil material was and is from failure conditions. Through these indicators, the zones which, by a probabilistic point of view, may be affected by a high level of damage or by a risk of damage have been localized.

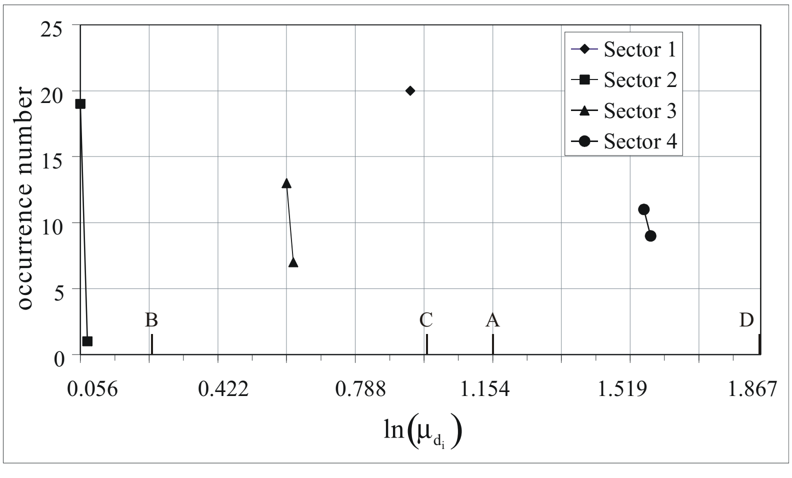

Figure 13. Distribution of the stress state Hazard regarding the case in which both small and large scale variability are assumed in both landslides body and landslides surface. Constant parameters A: sector 1, B: sector 2, C: sector 3, D: sector 4.

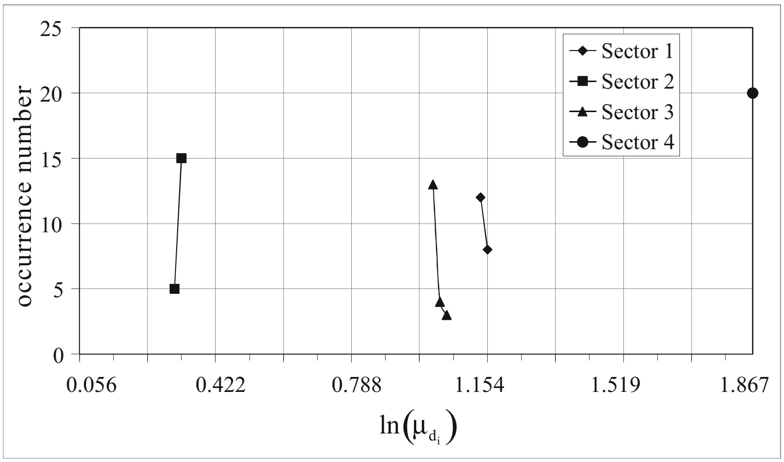

Figure 14. Distribution of the stress state hazard regarding the case in which only small scale is supposed.

An immediate implication of the aforementioned approach is the utility to perform a *Probabilistic Approach* to obtain a spectrum of responses and probabilistic distributions instead of a unique result. Another issue demonstrated by the analyses was that each sector of a system may be more or less affected by local variabilities. This suggests, with the help of the other geological tools, a spatial optimization of eventually further surveys, that partially excludes the zones which have been revealed to be less sensitive. Future improvements will allow the exploration of the effects of other statistics, the inclusion of point correlations, the inclusion of a fluctuation scale, and allow the provision of many more simulations in order to obtain a statistically suitable 'ensemble'.

Acknowledgements: the Authors are grateful to Dr. Monia Calista, Dr. Massimo Mangifesta and Dr. Barbara Di Giandomenico for the help in the editing.

REFERENCES

AA.VV. 1987. *La Grande Frana di Ancona del 13 dicembre 1982*. Numero Speciale, Studi Geologici Camerti, Università di Camerino, Italy.

BOX, G.E.P. & MULLER, M.E. 1958. *A note on generation of random normal deviates.* Ann. Math. Statist., **29**, 610-611.

CARRARA, F., D'ELIA, B. & SEMENZA, E. 1985. *Classificazione e nomenclatura dei fenomeni franosi*. Geol.Appl. e Idrog., **XX** (2), 223-244, Bari.

CRESCENTI, U., NANNI, T., RAMPOLDI, R. & STUCCHI, M. 1977. *Ancona: considerazioni sismo-tettoniche*. Boll. Geof. Teorica Appl., **73-74**, 33-48.

DE BOSIS, F. 1859. *Il Montagnolo: studi ed osservazioni*. Enciclopedia Contemporanea. Gabrielli, Fano (Italy).

FENTON, G.A. & VANMARCKE, E.H. 1990. *Simulation of Random Fields via Local Average Subdivision*. ASCE J. Engrg. Mech. **116**(8), 1733-1749.

KAGGWA, W. S. 2000. *Determination of spatial variability of soil design parameters and its significance in geotechnical engineering analyses*. Developments in Theoretical Geomechanics, Smith & Carter (eds*)*. Balkema, Rotterdam, 681-703.

ITASCA CONSULTING GROUP, INC. 2000. *FLAC-3D Manual*. Minneapolis, Minnesota: Itasca Consulting Group.

PASCULLI, A. & SCIARRA, N., 2002a. A *2D Mathematical and Statistical Modelling of Soils Structures*. Proceedings of 8th Annual Conference of the International Association for Mathematical Geology, 15-20 September 2002, Berlin, Germany, **1**, 111-116.

PASCULLI, A. & SCIARRA, N., 2002b. *Nodalizzazione ed interpolazione agli elementi finiti di eterogeneità strutturali in terreni granulari*. Applicazione ai pendii (in Italian). Atti Convegno AIGA-2003, 19-20 febbraio Chieti.

PASCULLI, A., CALISTA, M. & MANGIFESTA, M. 2006. *The effects of spatial variability of mechanical parameters on a 3D landslide study*. Fourth International Flac Symposium, May 29-31 Madrid, Spain; (in press).

SEGRÈ, C. 1919. *Criteri geognostici per il consolidamento della falda franosa del Montagnolo* . Boll. Soc. Geol. It., **38**, 99-131.

VANMARKE, E.H. 1977. *Probabilistic modeling of soil profiles*. Geotechnical Engineering*,* **103**(11), 1227-1246.