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Propagation analysis and risk assessment of an active complex landslide using a Monte Carlo statistical approach

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Abstract. The risk assessment of a rapid landslide is a difficult topic, even if based on the results of numerical analyses. The hypotheses on which every model is developed, the choice of rheological laws to be adopted, and the selection of soil parameters make the simulation results highly dependent on the user. This is particularly evident when there is no model calibration for the specific site or reliable information on soil properties. The paper presents a forecasting process obtained using a Monte Carlo approach in coupling with a propagation model developed with the SPH integration technique. The Monte Carlo analysis allows automatically carrying out a large number of simulations, each performed using an independent parameter set randomly selected within a priori assigned statistical distributions. The numerical results are then analysed with statistical tools to create a risk map based of the frequency of the unstable mass runouts. In this way, it is possible to reduce the user dependence of results and increase the examined potential scenarios. The procedure is here applied to the case study of the Sant'Andrea landslide, a slope movement active since several decades in the municipality of Perarolo di Cadore (Belluno, Italy). This complex slide involves an about 30 m-thick deposit of calcareous debris overlying anhydrite-gypsum rocks. Depending on the intensity and duration of rain, the slope alternates phases characterized by slow displacements and significant accelerations, then followed by a long relaxation period in which the displacement rate slowly regresses, without returning to the previous condition of movement. In recent years, the landslide activity has caused a progressive enlargement of the unstable area and a gradual increase of the basal rate, thus increasing the risk that the landslide may suddenly undergo to the collapse. Moving from the knowledge of the unstable volume, an SPH propagation model is used to study the area affected by the debris-flow runout. In particular, the analysis aims to define a statistical strategy to perform and interpret a large number of simulations and to create the consequent risk map. The analyses carried out lead to a satisfactory interpretation of the spatial variability of the deposit heights referred to the post-failure conditions, useful for the development of a risk analysis, from which a site risk map can be obtained.

1. Introduction

Slope instability is one of the most dangerous hydrogeological threats to the safety of people and infrastructures. The study of the propagation of rapid landslides often takes place through the use of numerical models capable of simulating large deformations. However, a dependence of the obtained results on the preventive choices made by the user is often relevant. In particular, the definition of rheological parameters assigned to the soil strongly affects the simulated deposits. This paper presents a statistical procedure aimed at reducing the dependence of the simulation outputs on the researcher's

choices, as well as allowing a sensitivity analysis of the runout obtained. The strategy is applied to the Sant'Andrea landslide, a large slope movement active close to Perarolo di Cadore village in North-Eastern Italian Alps. The landslide is characterized by alternation of slow movements and accelerations. Its potential collapse may produce a temporary dam on the river flowing at the base of slope and cause the flooding of the Perarolo village. In this analysis, the unstable volume determined by previous FEM-based analyses is used as input of an SPH propagation model adopted to simulate the hypothetical collapse. Reliable predictions on the landslide runout allow a site risk analysis and the definition of a consequent risk assessment plan.

2. Test site description

2.1. Geological setting

The Sant'Andrea landslide is located in the municipality of Perarolo di Cadore, in the Province of Belluno. It involves an area of 72000 m^2, suspended along the left bank of the Boite river just upstream the village (figure 1a). The moving mass represents a high hydrogeological risk for the urbanized site, in terms of number of elements at risk, and the potential hydraulic consequences in case of a paroxysmal collapse of the unstable mass.

The studied area is located in the region of the Dolomites and it is characterized by a Carnian (Upper Triassic) sedimentary succession, which is mainly represented by dolomitic and anhydrite limestones, dolomites and marls, locally affected by karstic cavities [1]. The various surveys performed over time, such as geological boreholes and geophysical investigations (refraction seismic and electrical tomography ERT) (figure 1b), led to the definition of thickness and spatial distribution of the geological units with a consequent reconstruction of a 3D geological model of the landslide.
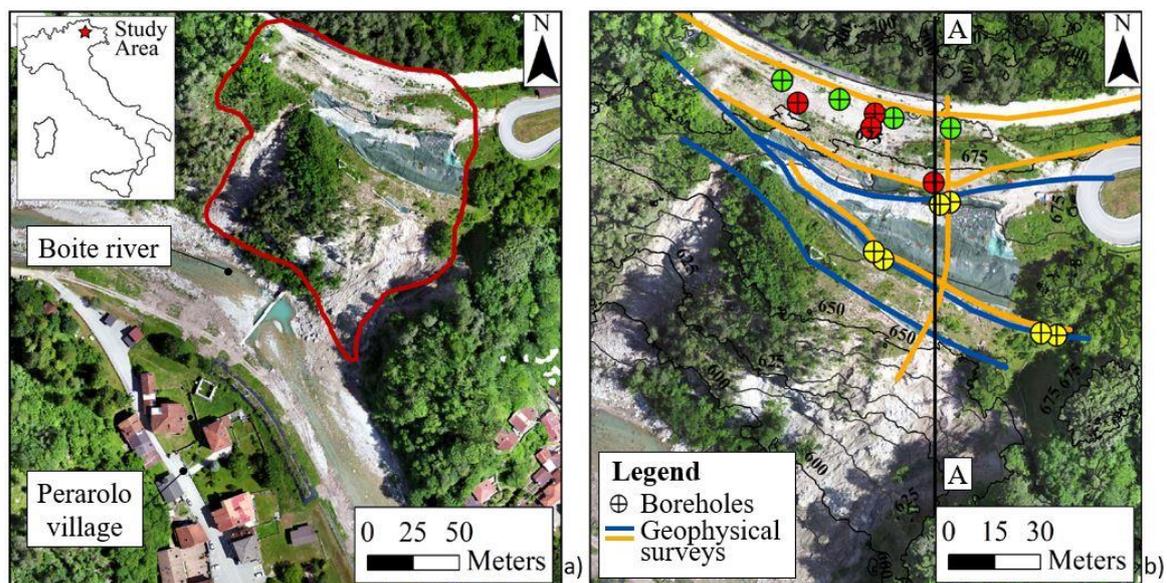

Figure 1. Sant'Andrea landslide site: (a) Location of Perarolo di Cadore village (NE Italy); (b) Geological boreholes (2019 in red; 2003 in yellow; 1987 in green) and geophysical investigations (2008 ERT in blue; 2003 seismic in orange) performed on the landslide area.

As reported in the geological cross section of figure 2, the Sant'Andrea landslide interests a 30 m thick deposit of clayey-calcareous debris composed by heterogeneous materials (layers A, B1 and B2) with various grain-size composition and geotechnical parameters. The debris mass slides over an anhydrite-gypsum rock mass, which is altered and fractured in its upper part (layer C) and more compacted and resistant in depth (layer D). A complex hydro-geological framework exasperates the slope state. Two circulation systems were identified within the moving mass (figure 2): a shallow one

interesting the permeable layer A and having the silty-clay layer B1 as impermeable base; a deep one involving the fractured gypsum layer C. It is well known that water is recognized to be a significant factor that influences the stability and mechanical properties of the gypsum rock [2, 3]. The infiltration of meteoric water from the upstream zone of the slope causes deep hydration and dissolution processes inside the anhydrite-gypsum rocks, especially in layer C, developing a plastic rheology of the gypsum lithology, which gives up to a gravitative process of the rock mass and to the general instability on the slope. Moreover, the gypsum dissolution induces an increase in voids, resulting in development of karst cavities and mm- to cm-thick microcrack net, crosscutting both the massive rock mass and the altered gypsum layer. In this way, the physical and chemical interaction of gypsum with the active circulation of groundwater makes the mechanical behaviour of this lithology quite unpredictable [4], leading to the hazard of a sudden collapse of the unstable mass.
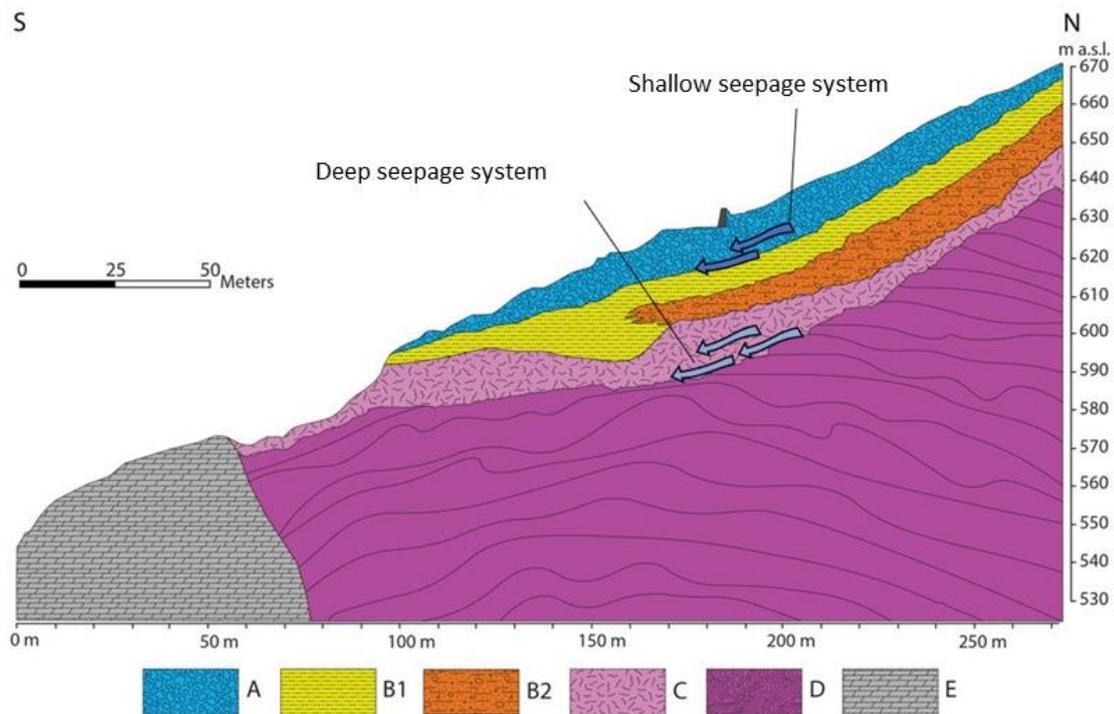

Figure 2. Landslide cross section A-A, with indications about the hydro-geological setting. The geological units are: sandy gravel deposits (A); silty-clay level (B1) and fine matrix sand and gravel level (B2); fractured gypsum layer (C); anhydrite-gypsum rock of the Travenanzes formation (D); Dolomia Cassiana (E) [5].

3. SPH-based propagation analysis

The predictions on evolution and propagation after the collapse of such a complex landslide are rather difficult. Various propagation models, among which the GeoFlow-SPH model [6] here adopted, are widely used to study rapid flow-like landslides and debris flows. In these models, the heterogeneous material involved in the flow is generally considered as an equivalent fluid [7], governed by simple rheological relations. The choice of the most adequate rheological law and the definition of the soil parameters require particular care, especially when considering a complex landslide such as that of Sant'Andrea, even if help can be given by back-analyses and calibrations widely available in the literature [8, 9, 10, 11, 12].

Another source of uncertainty is given by the precise not knowing of the volume in detachment, which can only be known if a failure has already occurred. In this case, a 3D Finite Element Model (FEM) is implemented and calibrated on the base of the observed displacement field. A preliminary FE-

based stability analysis permitted to estimate with a reasonable accuracy the potentially unstable volume, also considering the presence of the two seepage systems. The identification of an unstable mass with a total volume of about 97000 m³ resulted [13]. This volume is that introduced as an input in the propagation model.

3.1. Geometry and rheology

The geometry of the SPH model is created on the basis of the information gathered from the topographic survey of the area and from the geological and geotechnical surveys available. The basal topography is represented by a terrain mesh of 2 m resolution, which extends also outside of the landslide area. The source mass, deriving from the FEM stability analysis, is also discretized through a mesh with 1 m resolution. The entire sliding mass is considered governed by a frictional regime, well describable with the Völlmy rheological law (1955). In fact, the debris is constituted by a mixture of granular particles developing a frictional behaviour, englobed in a fine matrix with a viscous behaviour. Völlmy law requests the calibration of two parameters, namely the friction coefficient μ, equal to the tangent of the base frictional angle, and the turbulent factor ξ.

The ranges of the Völlmy parameters are chosen on the basis of indications provided by the scientific literature [8, 14, 15, 16] and according to the grain-size composition and geotechnical properties of the soil involved in the possible collapse. As underlined in [8], values between 0.05 and 0.25 can be used for the basal friction coefficient and between 200 and 1000 m/s² for the turbulence coefficient, depending on the flow type needing to be simulated.

3.2. Monte Carlo analysis

In the case of the Sant'Andrea landslide, no significative collapse occurred up to now, so a back analysis is not possible. For this reason, a statistical selection of the soil parameters is performed to fill the gap of model calibration and reliable information of soil properties. In this way, it is possible to reduce the user dependence of results and enlarge the examined potential scenarios. The statistical strategy aims at performing a large number of simulations using a Monte Carlo approach. Each simulation is performed using an independent parameter set obtained from a random selection within a priori assigned statistical distributions. The choice of randomly varying the parameters having a Gaussian distribution allows to include scenarios that could rarely occurs, but which are set at a lower frequency of occurrence. The incomplete characterization of the material involved in the landslide, the need to use an equivalent single-phase formulation, the strong dependence of the behaviour of the soil on the presence of water, in fact, require to consider a wide enough range of potential scenarios.
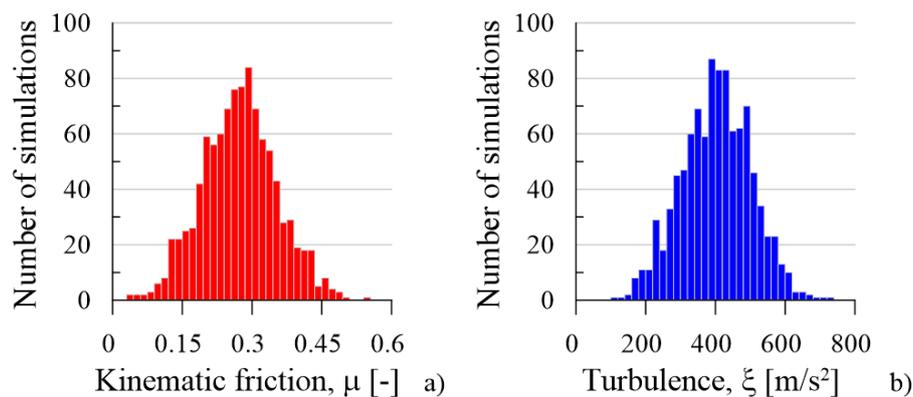

Figure 3. Statistical distributions for (a) the kinematic friction and (b) the turbulence coefficient.

For both the rheological parameters, a Gaussian distribution of frequency is assumed. A mean value and a standard deviation are then assigned based on values largely adopted in literature, thus allowing the definition of 1000 couples of parameters randomly selected. The obtained distributions are visible

in figure 3 for (a) the kinematic friction coefficient (mean value = 0.27, std = 0.08) and (b) the turbulence coefficient (mean value = 400 m/s², std = 100 m/s²). A specific script is performed to create 1000 folders, each of which containing the input files necessary for the simulations. Basal topography and unstable mass are kept common to all simulations, while the parameters are updated according to the extractions obtained from the relative Gaussian distributions.

All simulations are automatically performed and, at the end of each, the outputs of the final soil deposits are extracted. Globally, testing took around 10 hours to complete.

4. Result and discussion

It is possible to interpret the results by plotting the deposit heights at the end of the debris flow directly on an aerial photo of the site. The information is expressed using a 1 m square grid, containing the height of soil deposit obtained from each simulation in that specific position. 1000 deposit maps thus constructed are therefore obtainable. Each cell of the grid varies its content according to the simulation considered.
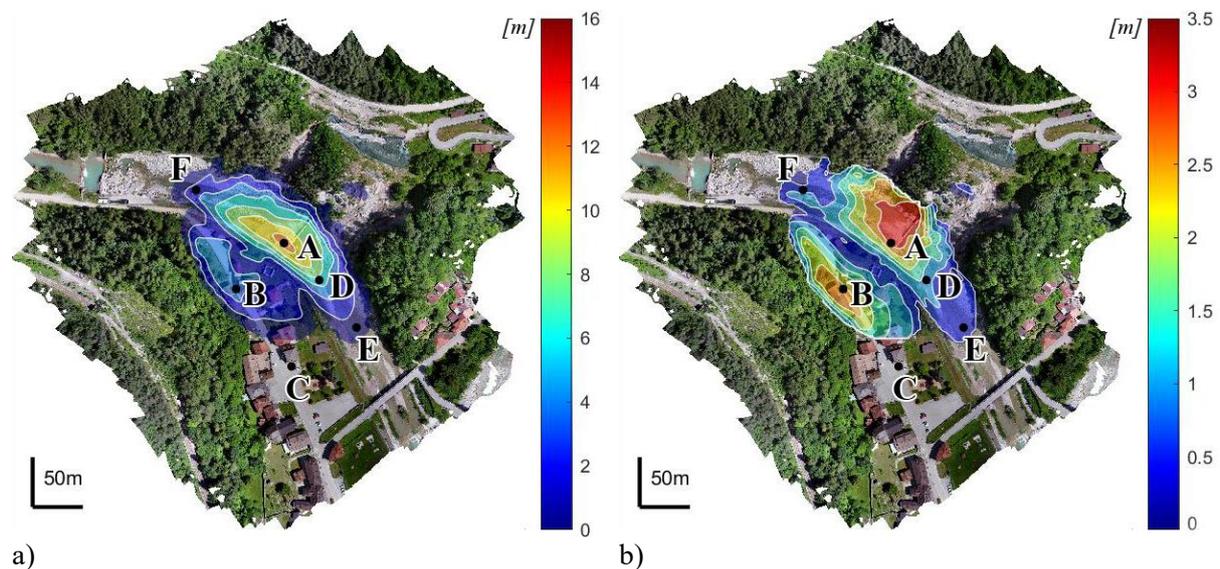

a)   b)

Figure 4. Plot of the (a) median values and (b) standard deviations of the height soil deposited, for each 1 m squared position of the site.

A first interpretation of the results is possible considering the average trend of the results. It is in fact possible to plot for each cell the median value among the 1000 obtained globally in that position. In figure 4a, the median value of the deposit heights is presented: its maximum value is observable in correspondence of the landslide toe, while moving away, its value gradually decreases. On the same figure some characteristic points are also indicated with letters from A to E. Point A represents the position of maximum thickness of collapsed mass, in the center of the Boite stream, facing the landslide body. Points B and C instead indicate two areas of the town which are therefore very sensible positions, if hit by the landslide. Finally, points D, E and F represent points along the stream bed, placed upstream and downstream of the instability at different distances, which well express the extent of the landslide.

To evaluate the variability of the results, figure 4b presents the standard deviation observed in each 1 m cell. The maximum variability occurs right at the toe of the landslide and in the center of the Perarolo village. Note that the standard deviation is plotted only in cells where the median has a non-zero value. However, even outside the colored area, some material arrives for some simulations, such as in point C. To have a better interpretation of the results in the six chosen positions, figure 5 reports the distribution of the deposit heights for each of them. First of all, it should be noted that only for points A and F the number of simulations with a not null deposit value ($N_{Hs\neq0}$) is equal to 1000. In point B $N_{Hs\neq0}$=881, while

at point C is only 237. Furthermore, the distribution variance gives an indication of the central value reliability. For example, point E shows a very evident peak, with a deposit height greater than 3.5 m even in a third of the total simulations. The distribution of point B, on the other hand, is less spicy, showing variable heights between 0.5 m and 9 m, without particularly evident peaks. The median value considered in figure 4, therefore, can be representative of the cells in which the peak is evident, but risks underestimating the deposit in the positions where the distribution curves are flatter.

For this reason, it is considered appropriate to build two further maps. The first (figure 6a) contains a percentage frequency, i.e. how many simulations, above the total, showed a final deposit greater than 1 m in that cell. Obviously, this map provides an indication of the area most likely to be covered by the material, but it does not allow to estimate the amount of deposits in quantitative terms. A second map (figure 6b) instead allows to have a clearer evaluation of the deposit heights that, with high probability, can reach a certain position. To construct this map, a percentile value of 95% of the distribution of deposit heights of each cell was considered. This is equivalent to consider, for each square meter, a deposit value that is exceeding with a probability of occurrence of 5%.

Finally, it is possible to plot the trend of deposit heights as a function of the rheological parameters. In particular, figures 7a and b show the deposit height at points A to D as the kinematic friction parameter and the turbulence coefficient vary. The variation of the kinematic friction produces, in each position, a curve with an evident peak of the deposit height; for example, in point A, a maximum deposit height of almost 16 m is observed for kinematic friction around 0.4, whereas points B and C show the peak values for lower friction, around 0.15. This highlights that the friction angle strongly affects the results of the simulations. On the contrary, figure 7b does not show a clear dependence of the deposit height in every position in relation to the turbulence factor. At point A, for example, for an average turbulence value, equal to 400 m/s^2, heights vary between 16 and 4 m. This is also evident for the other positions considered (points B, C and D).
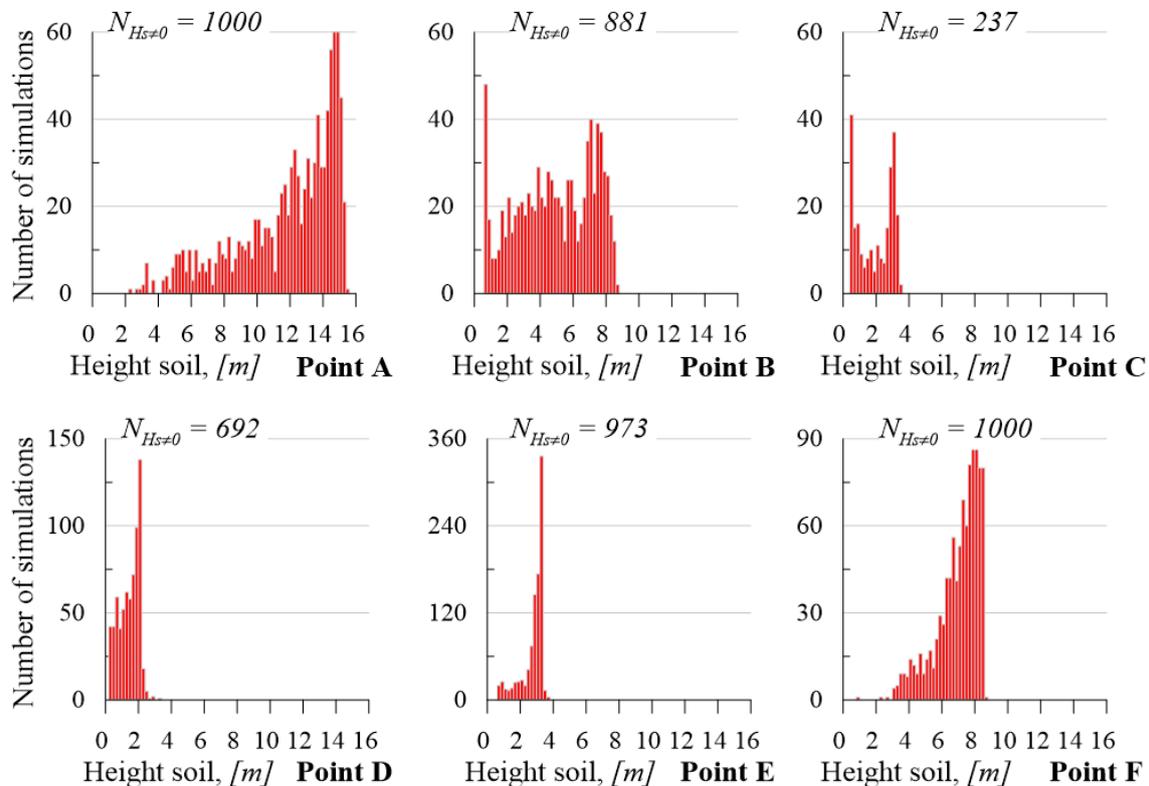

Figure 5. Height soil statistical distributions on positions from A to F.

5. Conclusion

The analysis of the possible evolution of Sant'Andrea landslide allows to predict the area potentially involved in the post-collapse run out. The estimation of the spatial variability of the deposition heights develops a site frequency map. The execution of a large number of simulations, with parameters drawn in a random manner from Gaussian distributions with imposed mean and standard deviation values, allows to reduce the dependence of the results on the user's choice. Furthermore, it highlights the sensitivity of the results to each rheological parameter. However, the interpretation of the results of a large number of simulations is not unique and several maps can be created. For example, the map of the median deposit heights in the various positions of the site can be plotted. The variability of these results can also be included in the interpretation by analysing the correspondent standard deviations. A spatial estimate of the deposit heights can instead show the frequency with which the simulations reach a certain position. Finally, the most conservative interpretation of analysis results is that considering the deposit height value that does not exceed 95% of the occurrence probability. In this way, in fact, a frequency map indicated the area that can be affected by the run-out with a very high probability. Obviously, this map does not express a real distribution of the debris on the area, but, for each position, which height of deposited material can be considered reasonably maximum, in case of slope collapse.
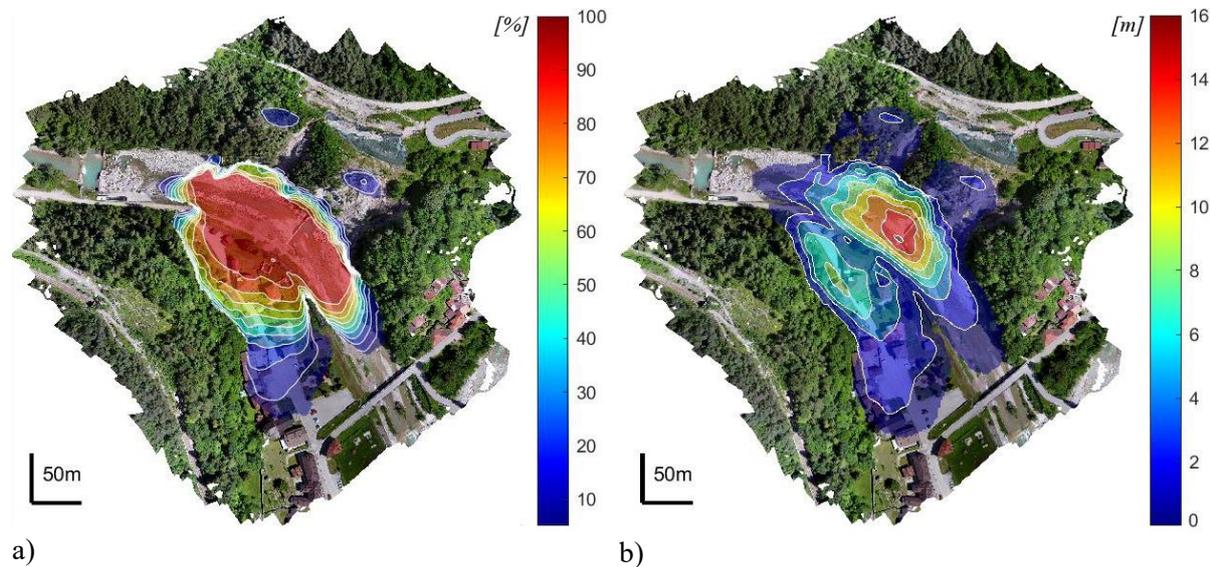

Figure 6. (a) Percentage of simulations reaching that area; (b) Height soil distribution considering the 95% percentile for each 1 m squared position of the site.
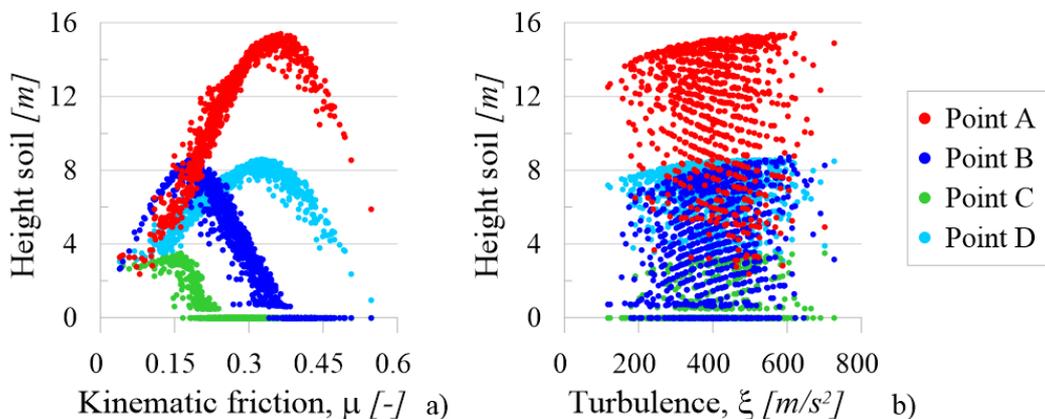

Figure 7. Plot of dependence of height soil on the variation of the Völlmy parameters (a) kinematic friction coefficient, (b) turbulence coefficient.

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