

# Susceptibility analysis of rapid flowslides in southern Italy

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**Abstract.** Qualitative and quantitative estimation of distribution of the existing landslides or that could occur inside a determined area is named landslide susceptibility. The zoning of landslide susceptibility consists of inventory of landslides occurred in the past and identification of the areas where the landsliding could occur in the future. The paper shows the results of a study of fast flowslides susceptibility performed on an area placed between Scilla and Favazzina (RC) regularly and historically interested by rainfall and in some cases by earthquake induced landslides. The trend of inclination and lithological features of the potential detachment zones has been analyzed at 1:5.000 scale. Classes of inclinations, where the most part of detachment zones are clustered, have been identified and the distribution of these classes for each lithological type has been graphed. Among all surveyed events, the inclinations and lithological features of the detachment zones similar to those of the events occurred in the 2001 and 2005 have been found. Finally, in order to evaluate the susceptibility of the area, the paths of flowslides have been evaluated by numerical simulations using the SPH model.

## 1. Introduction

Flowslides are landslides consisting of events of mass transports constituted of water and solid material triggered by natural factors, mainly heavy rains and earthquakes, but also by human activities. They occur periodically on established paths, usually gullies and first or second order drainage channels. Thus, flowslide vulnerability is specific to a given path and a deposition area (“debris fan”). This, and the periodicity of occurrence at the same location, influences the methodology of vulnerability studies and contrasts with related phenomena, such as debris avalanches, whose occurrence is not bound to an established path [1]. The interaction between fluid and solid component plays a key role in the physics of the phenomena and makes them particularly destructive. In these phenomena the two main components of the mixture, water and solid particles, can be present in different proportions and the behaviour can belong to the movements of the slope or the flooding depending on the concentration of the mixture. The separation between the two types of phenomena is very difficult. The most widely used classification is the system proposed by Varnes [2], [3] and modified by Cruden and Varnes [4]. Hungr et al. [1] proposed an update of the Varnes classification to modify the definition of landslide-forming materials and to correlate the terminology of landslides with the mechanical behaviour.



Nowadays flowslides are responsible for some of the largest landslide disasters [5]. Furthermore, population growth has driven development further into debris-flow-prone areas, increasing risk from this hazard [5]. For these reasons, a large part of research on risk of flowslides has been performed to in - depth understand of the susceptibility analysis. Many of these studies have focused on the physical characteristics and processes of flowslides. These included geologic settings, triggering mechanisms, transport processes, deposition characteristics, and mitigation options in order to identify the most appropriate strategies for the mitigation of landslide risk to which people and properties (structural and infrastructural facilities) are exposed.

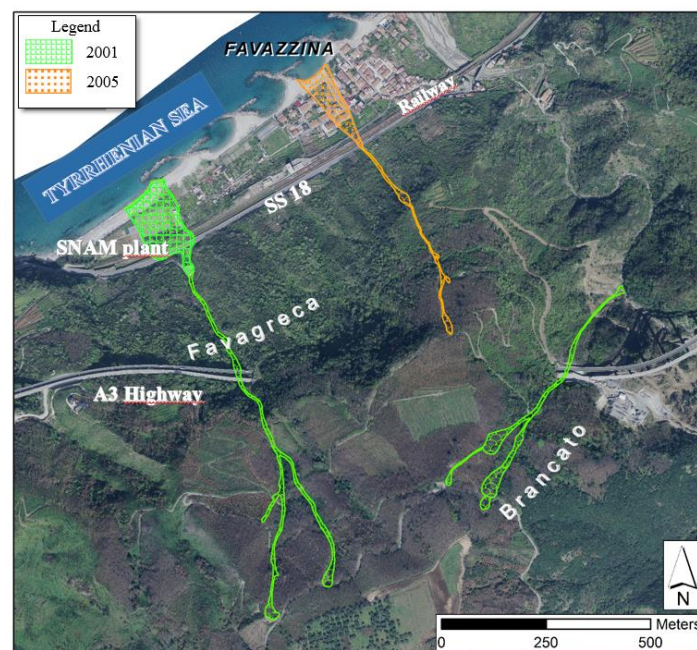
The paper shows the results of a study of rapid flowslides susceptibility performed at large scale on a wide area placed between Scilla and Favazzina (RC), regularly and historically interested by rainfall-induced landslides and sometimes also by earthquake landslides. The paper is developed on the base of geomorphologic data, slope gradients, lithological maps, and numerical approach. In particular, the aim of the research is to provide susceptibility maps drawn for a specific rheological behavior of the material involved in the landslides and a specific erosion coefficient on the bottom of the channel.

The study is a further development of a research on analysis of areal scale of landslides induced by rainfall that the Department DICEAM has been carried out for a long period [6], [7], [8], [9].

## 2. Analysis of the events classified as fast flowslides in the south of Italy

The analysis of the flow-like landslides has been performed using the data provided by the Basin Authority of the Calabria Region, updated to 2006 and data available on the National Geoportal. These data have been catalogued according to IFFI Project (Inventory of landslides in Italy) whose target is to create a single information system for the landslides in Italy and the homogenization of the national data.

The area chosen as study case is the zone between Scilla and Favazzina, affected by several events of flow-like landslides. In particular, two events, occurred in May 2001 and in March 2005 (figure 1), produced extensive damage involving various lifelines. The flowslides in the area are generally translational landslides involving the superficial and weathered part of the metamorphic bedrock; they occur upslope to the channels, concomitant with very intense rainfalls. The landslides mass is channelled and fluidized by stream waters. Previous reconstructions have shown that the volumes at the end of the propagation are tripled respect to detachment volumes [10].



**Figure 1** – 2001 and 2005 flow-like landslides events in Favazzina.

Figure 1 shows the detachment zones of the flowslides, propagation and accumulation areas and the infrastructures involved during the events. On 12 May 2001, two translational landslides were triggered by heavy rainfalls at the head of the Favagrega River, respectively at 570 and 550 m above sea level in correspondence of two incisions that are joined at about 300 m a. s. l. The movement of the translational landslides turned into a rapid flow-like landslide that hit the SNAM station of the methane pipeline, the main road SS 18 and the railway causing the derailment of the intercity train Turin - Reggio Calabria. A second smaller flow slide triggered in an adjacent valley above the A3 highway. On 31 March 2005, a similar phenomenon has been activated in the valley near to Favazzina village, causing several damages to the highway and the railway, causing the derailment of the intercity train ICN Reggio Calabria – Milan.

The soil involved are weathered covers of metamorphic bedrock that have thickness ranging from centimetres to one meter (Figure 2).



**Figure 2** – Typical weathered covers of metamorphic bedrock.

Because of the vegetation cover and the inaccessibility of the place, the weathered covers are not easy to observe. The geomorphic characteristics of the area have been determined by in situ surveys and by photo-interpretation of flight Calabria 2001 stereoscopic frames (scale 1: 15.000 and 1: 18.000).

The high relief energy make possible the gravitational sliding that mark the slope with frequent episodes, mainly present at the head of streams. The landslides affect the weathered covers of metamorphic bedrock, and often involve in their movement also the man-made terraces for agricultural purposes. The instabilities turn into debris flows that, channelling into valley, reach the coast at the base of the slope, involving traffic road and railway. In the area, the most part of sediments that reach the coast and those that forms the area behind the beach were originated by these processes. From hydraulic point of view, it must be pointed out the strong erosive and transport capacity of the drained water of the streams that are able to transport disruptive amount of water and debris.

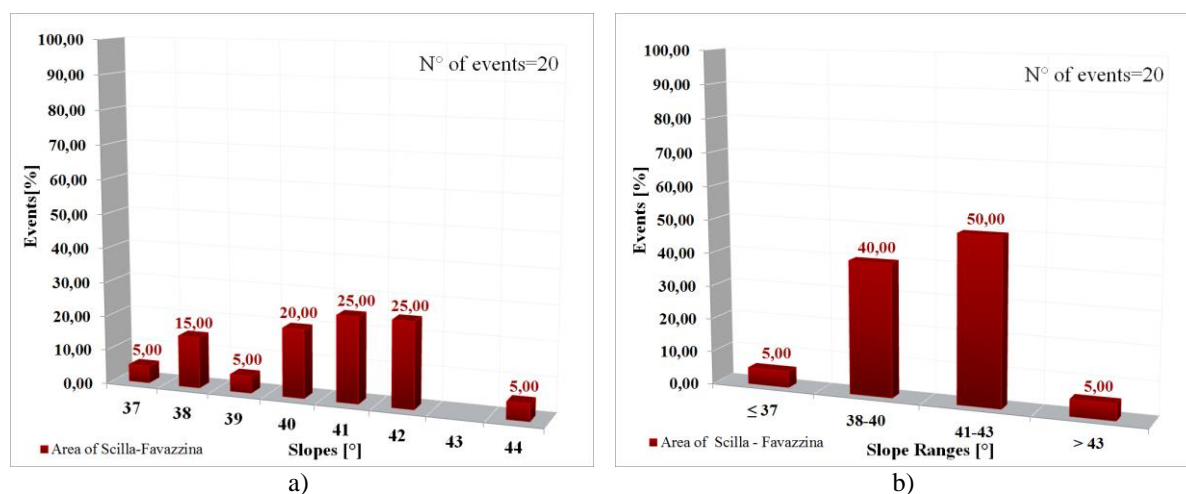
The total number of real events occurred in the area, obtained using the data provided by the Basin Authority of the Calabria Region and data available on the National Geoportal, is equal to 20. In order to characterize the collected events, inclinations and lithological features of the detachment zones have been used as susceptibility descriptors. The inclinations has been analysed at 1:5.000 scale and their values, and relative lithological features are reported in table 1.

**Table 1** – Inclinations and lithological features of the real flow-like landslides.

Landslide N°	i [°]	Lithological features
1	42	Paragneiss, Gneiss, Biotitic schists
2	41	Paragneiss, Gneiss, Biotitic schists

3	42	Paragneiss, Gneiss, Biotitic schists
4	41	Debris
5	40	Debris
6	40	Paragneiss, Gneiss, Biotitic schists
7	38	Gneiss occhiadini
8	42	Gneiss occhiadini
9	38	Gneiss occhiadini
10	42	Gneiss occhiadini
11	44	Gneiss occhiadini
12	39	Paragneiss, Gneiss, Biotitic schists
13	37	Paragneiss, Gneiss, Biotitic schists
14	42	Paragneiss, Gneiss, Biotitic schists
15	41	Paragneiss, Gneiss, Biotitic schists
16	40	Paragneiss, Gneiss, Biotitic schists
17	41	Paragneiss, Gneiss, Biotitic schists
18	40	Paragneiss, Gneiss, Biotitic schists
19	41	Paragneiss, Gneiss, Biotitic schists
20	38	Paragneiss, Gneiss, Biotitic schists

The variation of the frequency of the events versus the slopes and the classes of slopes are shown in figure 3a and 3b. In particular, the figure 3b shows the slopes clustered in four classes:  $\leq 37^\circ$ ,  $38^\circ$ - $40^\circ$ ,  $41^\circ$ - $43^\circ$  and  $>43^\circ$ .

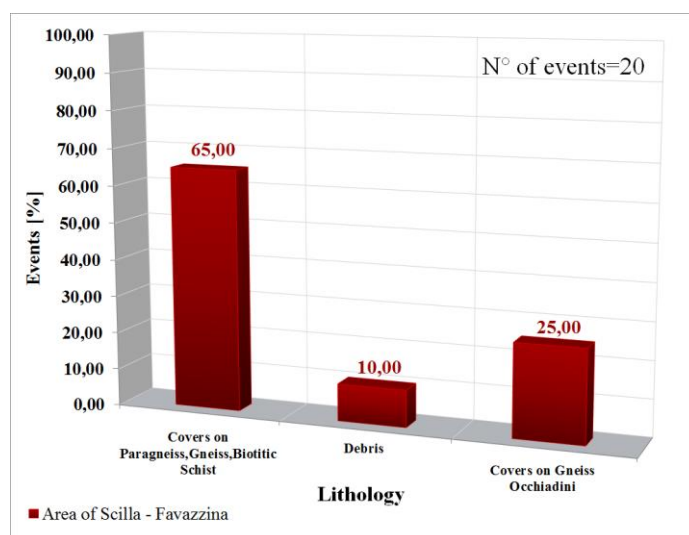


**Figure 3** – Histograms Frequency number of real events – Slopes (a); Frequency number of real events – Slope Ranges.



It can be noticed that the most part of the events occurs on slopes of  $41^\circ$  and  $42^\circ$  (Figure 3a) and in the classes  $38^\circ - 40^\circ$  and  $41^\circ - 43^\circ$  (Figure 3b). In areas with slopes less than  $37^\circ$  and greater than  $43^\circ$  the number of events is small and equal to 5%.

The second parameter used as susceptibility descriptor of the flowslides has been the lithology of the areas affected by landslides. The statistical distribution of lithologies affected by the events of flowslides is shown in figure 4.



**Figure 4** – Histogram of frequency of the real events per lithology.

It can be noticed that paragneiss, gneiss and biotitic schists are involved for the 65% of the events; the 25% of the events occurred on gneiss occhiadini and only the 10% of the events occurred on debris.

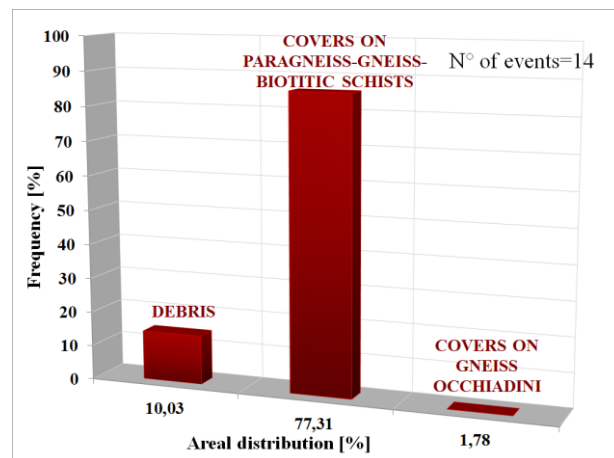
It has also been determined the areal incidence of each type of lithology compared to the total area, as a function of the frequency of the number of events. This analysis was conducted by means of a lithological chart at scale 1:5000.

The area is approximately equal to  $4,80 \text{ km}^2$ . The areal distribution of each lithology affected by events of flowslides is shown in the table 2.

**Table 2** – Areal distribution of lithologies.

Total area [km <sup>2</sup> ]	Lithology	N° of events	Frequency of the events [%]	Lithology area [km <sup>2</sup> ]	Areal distribution [%]
4,76	Debris	2	14	0,48	10,03
	Covers on Paragneiss– Gneiss–Biotitic schists	12	86	3,68	77,31
	Covers on Gneiss Occhiadini	0	0	0,08	1,78

It can be noticed that paragneiss, gneiss and biotitic schists cover the 3.68% of the examined area.

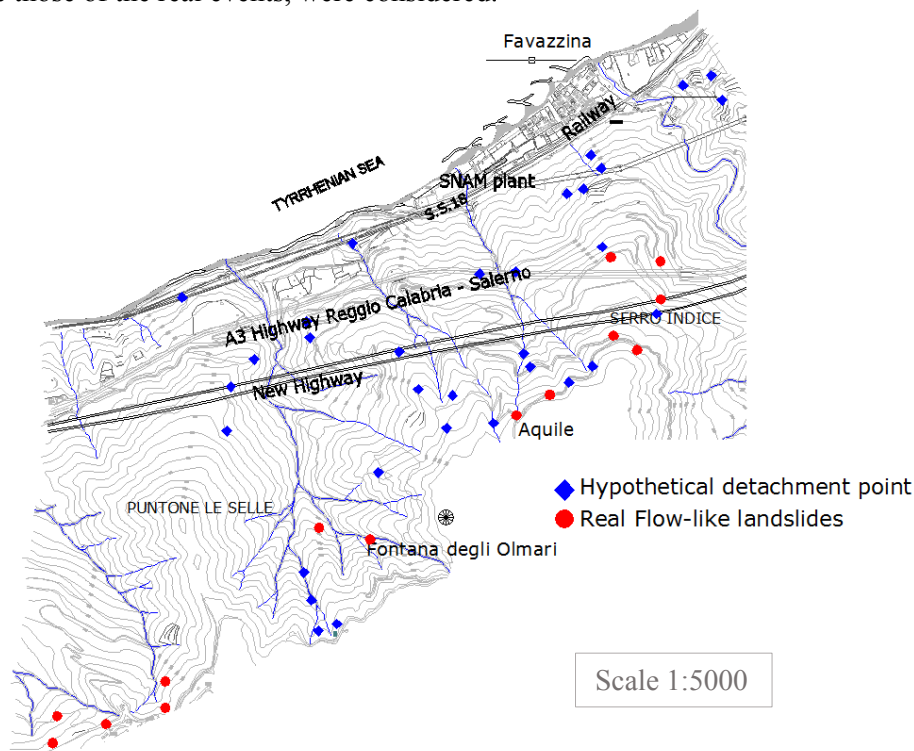


**Figure 5** – Histogram of areal distribution of the lithology versus the frequency of the events.

Figure 5 shows the areal distribution versus the frequency of events. As expected, the areal distribution is equal to 77,31% on the paragneiss, gneiss and biotitic schists with 86% of frequency of the events, while it is equal to 10,03% on debris with events frequency equal to 14% and the areal distribution is equal to 1,78% on gneiss occhiadini but no events occurred here.

### 3. Susceptibility analysis of the representative area of Favazzina

Analysis of the real events in the study area allowed to obtain the inclination values and lithological features that may be affected by flow-like landslides. Then, hypothetical detachment zones have been identified (Figure 6) taking into account points with inclinations and lithological features similar to those of the real events, and geomorphological evidences such as crowns, deep eroded gullies, and steep slope. The total number of so obtained points was 65 but only the points with inclinations between  $37^\circ$  and  $44^\circ$  degrees, like those of the real events, were considered.



**Figure 6** – Map of the hypothetical detachment points.

In figure 6, the blue squares represent the hypothetical detachment points with the same inclinations and lithological features of the real events, while the red circles represent the real flow-like landslides. 32 hypothetical detachment points have been individuated.

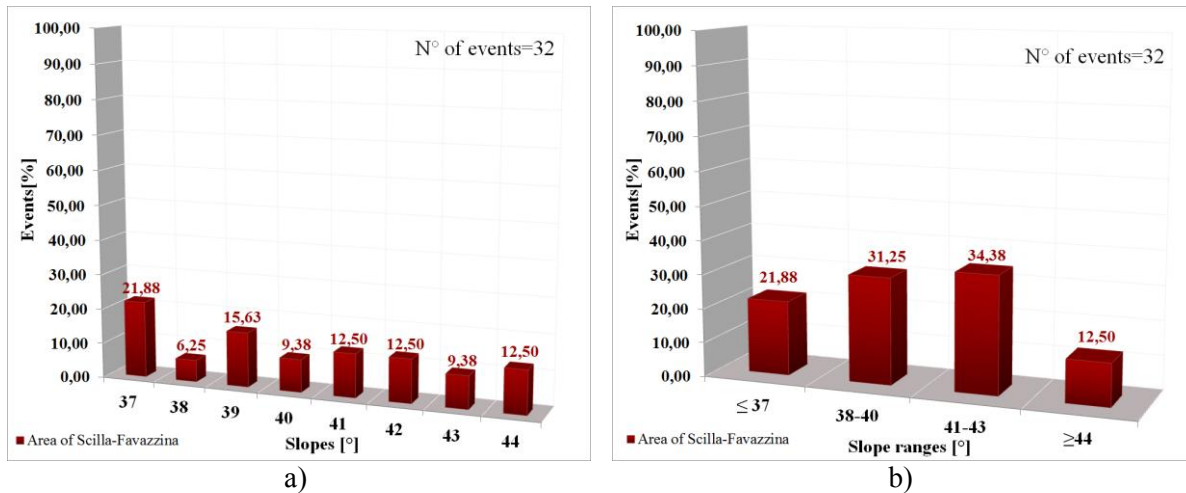
### 3.1. Statistical analysis

The slope values, the lithological features and the geomorphological evidences of each detachment point is listed in table 3, where the paragneiss, gneiss and biotitic schists have been clustered and called paragneiss because the covers on these rocks are the same and they are weakly clay sandy silts.

**Table 3** – Slopes, lithological features and geomorphological evidences of the hypothetical detachment points.

Detach. point	i [°]	Lithological features	Geomorphological evidences
1	37	Covers on Paragneiss	Crown
2	43	Covers on Paragneiss	Crown
3	37	Covers on Paragneiss	Crown
4	42	Covers on Paragneiss	Deep eroded gully
5	40	Covers on Paragneiss	Deep eroded gully
6	44	Covers on Paragneiss	Deep eroded gully
7	37	Debris	Crown
8	39	Debris	Crown
9	39	Covers on Paragneiss	Collapse slope
10	41	Debris	Deep eroded gully
11	41	Covers on Paragneiss	Collapse slope
12	37	Covers on Paragneiss	Deep eroded gully
13	43	Covers on Paragneiss	Steep slope
14	44	Covers on Paragneiss	Crown
15	38	Covers on Paragneiss	Collapse slope
16	42	Covers on Paragneiss	Deep eroded gully
17	39	Covers on Paragneiss	Crown
18	40	Covers on Paragneiss	Crown
19	38	Continental deposits	Crown
20	37	Continental deposits	Crown
21	44	Covers on Paragneiss	Crown
22	37	Covers on Paragneiss	Crown
23	37	Covers on Gneiss occhiadini	Deep eroded gully
24	41	Covers on Gneiss occhiadini	Deep eroded gully
25	39	Covers on Paragneiss	Crown
26	43	Covers on Paragneiss	Crown
27	41	Covers on Paragneiss	Steep slope
28	42	Covers on Paragneiss	Crown
29	39	Covers on Paragneiss	Crown
30	42	Covers on Paragneiss	Crown
31	44	Covers on Paragneiss	Crown
32	40	Covers on Paragneiss	Crown

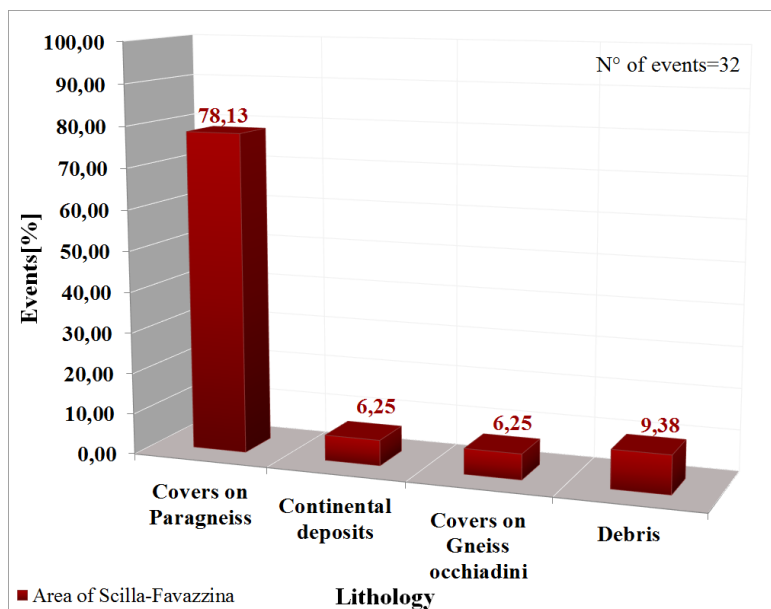
As for the real events, the statistical distributions of the frequency of the hypothetical events versus the slopes (a) and classes of slopes (b) have been graphed.



**Figure 7** – Histograms Frequency number of hypothetical events – Slopes (a); Frequency number of hypothetical events – Slope Ranges.

Figure 7 (a) shows that greatest number of events (21,88% and 15,63%) occurred on slopes equal to 37° and 39°. The histogram in figure 7 (b) indicates, clearly, the most part of the possible events occurred on slopes in the ranges 38°-40° (31,25%) and 41°-43° (34,38%).

Also in this case, the statistical distribution of lithologies has been graphed in function of the frequency of the number of events (Figure 8).



**Figure 8** – Histogram of the frequency of the hypothetical events per lithology.

The most involved lithology has been covers on paragneiss with frequency of the events equal to 78,13%; the debris have been affected only by 9,38% of events. A few number of events occurred in other lithologies. This happened because in the area especially paragneiss outcrop (Table 2).



### 3.2. Numerical simulation using SPH model

As mentioned previously, the analysis of the representative area of Favazzina aims to define the parameters to use in order to define the susceptibility of the area. In addition to the inclination and lithology parameters representing the common indices for the trigger phase of the flow-like landslides, it is important to focus on the propagation phase which identifies the runout area and the flow velocity. The prediction of both runout distances and velocity of fast flowslides by means of mathematical modelling allows to identify the elements exposed at risk. It provides a mean to estimate the vulnerability and it provides the suggestions for the choice of appropriate mitigation measures.

Most of the current numerical models, available in literature, are based on grids, like finite differences or finite elements and volumes. An interesting and powerful alternative to these methods is provided by 'meshless' numerical methods that have been developed in the past decades. The key idea of the meshfree methods is to provide accurate and stable numerical solutions for integral equations or partial differential equations with all kinds of possible boundary conditions with a set of arbitrarily distributed nodes (or particles) without using any mesh that provides the connectivity of these nodes or particles [11]. Smoothed particle hydrodynamics (SPH) [12] [13], as a meshfree and particle method, was originally invented for modelling astrophysical phenomena, and later widely extended for applications to problems of continuum solid and fluid mechanics because of relatively strong ability to incorporate complicated physical effects into the SPH formulations. The earliest applications of SPH were mainly focused on fluid dynamics related areas and has also been applied to model the propagation of catastrophic landslides. In this paper a model, based on the SPH method and proposed by Pastor [14], able to simulate the propagation of fast debris flows is presented.

The mathematical model is based on the mixtures theory and the numerical model is defined depth integrated model because its equations are integrated along the vertical axis. Finally, a rheological model has added in order to describe the fluidized geo material [14].

Like previously mentioned in the study area two particularly damaging landslides occurred: 2001 and 2005 events. In particular the numerical analysis was performed by the use of the results of PhD thesis on "Numerical modelling of the phenomena of debris flows" [15] that analyses the real flowslide occurred on May 2001. One of the main difficulties encountered when modelling run out of landslides is the selection of the rheological model and its material parameters. In some cases, as in the present study, it will be possible to obtain the soil properties with rheometer or viscometer tests, like in the case of muddy materials without large granular particles. Effectively, the analysis carried out on the soil where hypothetical points are located showed that it is the same of the involved soil by 2001 flowslide, a sandy silt with a high content of fine-grained material (60% of silt and clay).

In the PhD thesis was carried out a calibration of rheological parameter and the viscous Bingham law was the rheological model that better approximated the real event. The rheological parameters of water-sandy silt mixtures used in the PhD was carried out by laboratory test and the simulation results was compared with real evidences. The numerical analysis carried out in the present study take into account some difficulties such problems related to initial conditions of the mobilized geomaterials, problems related to the behavior of the fluidized material, problems related to interaction between propagating material and the basal surface (erosion). After defining the rheological model, considering the results of PhD thesis, in the present study was carried out different calibration analyzes regarding: sensitivity to initial mass, sensitivity to the number of points describing landsliding mass, sensitivity to DTM grid spacing and calibration of erosion factor.

In particular, the analysis carried out on the 2001 landslide indicated that the solid concentration by volume was equal to 60% and the total volume of the mass was equal to 1130 m<sup>3</sup> [10]; a calibration analysis was carried out to determine the best rheological parameters values, varying the critical shear stress  $\tau_c$  between 19 and 190 [Pa] and the viscosity coefficient  $\mu$  between 4 and 40 [Pa·s]. In the numerical model, the Hungr equation [16] is implemented depending on  $E_s$ , defined as the "growth rate". Also this erosion coefficient was calibrated varying his values between 0.0001 and 0.002 m<sup>-1</sup>.

In the present paper these calibration analysis weren't reported because the principal aim is to describe and draft the susceptibility map.

The mathematical relations which represent Bingham model have been the following:

$$\tau_c = 0,2959 \exp(0,1293 \cdot C_v) \quad (1)$$

$$\mu = 0,0090 \exp(0,1666 \cdot C_v) \quad (2)$$

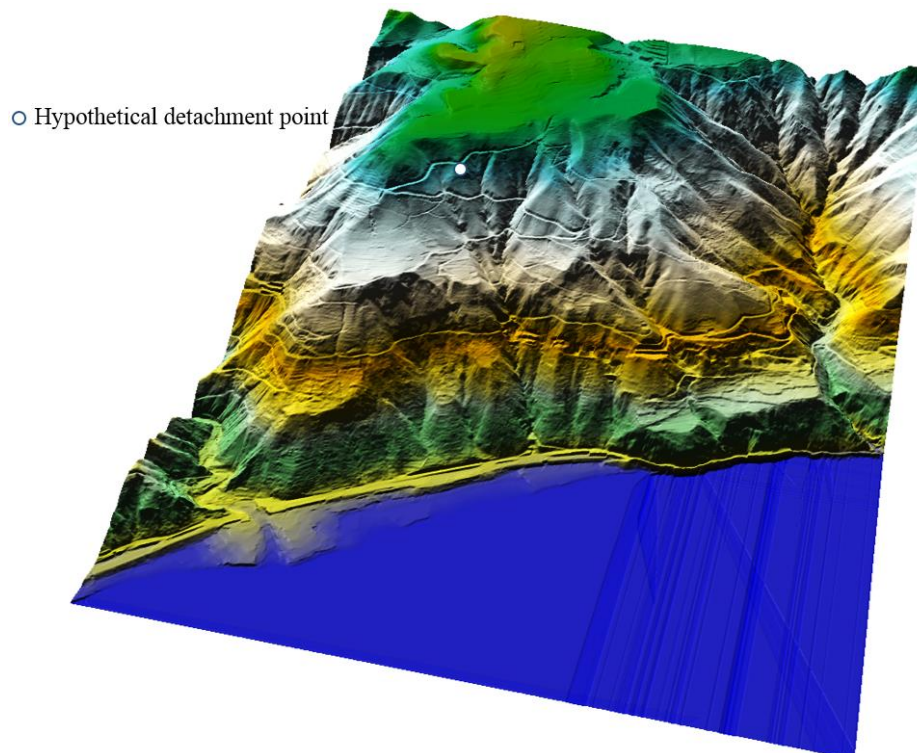
$\tau_c$  is the critical shear stress,  $C_v$  is the solid concentration by volume and  $\mu$  is the viscosity coefficient. The values used in the following numerical simulation of these parameters are listed in table 4.

**Table 4** – Bingham parameters.

$C_v$ [%]	$\tau_c$ [Pa]	$\mu$ [Pa·s]
60	692,5	197,4

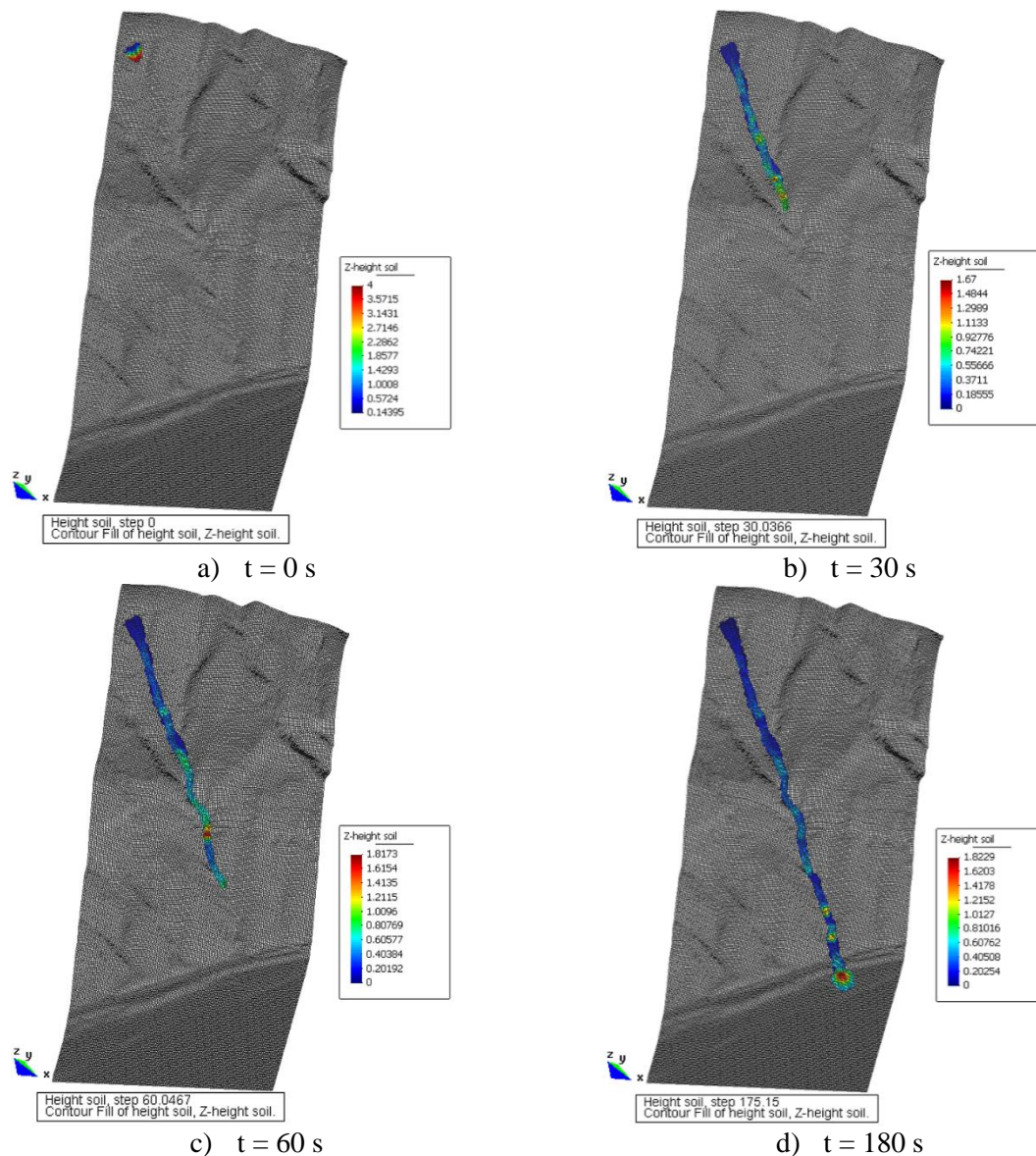
While the erosion rate  $E_s$  is equal to  $0,002 \text{ m}^{-1}$ , according to the best result of the calibration analysis.

Figure 9 shows the digital terrain model of the whole studied area of Favazzina and a hypothetical detachment point is pointed out.



**Figure 9** – Digital Terrain Model of Favazzina.

The modelling results of the hypothetical detachment point is shown in figure 10. The simulation time is equal to 180 seconds, assuming a propagation velocity, approximately, equal to 6 m/s; the behaviour is undrained and the bed is erodible. The figures 10 a, b, c and d show the height soil in 4 different times: 0, 30, 60 and 180 seconds.



**Figure 10** – Simulation results of hypothetical detachment point. a) Landslide position at 0 s; b) landslide position at 30 s; c) landslide position at 60 s; d) landslide position at 180 s.

It can be noticed that the topography has been reproduced in detail; the landslide is well channelled along the path and the accumulation area is well defined.

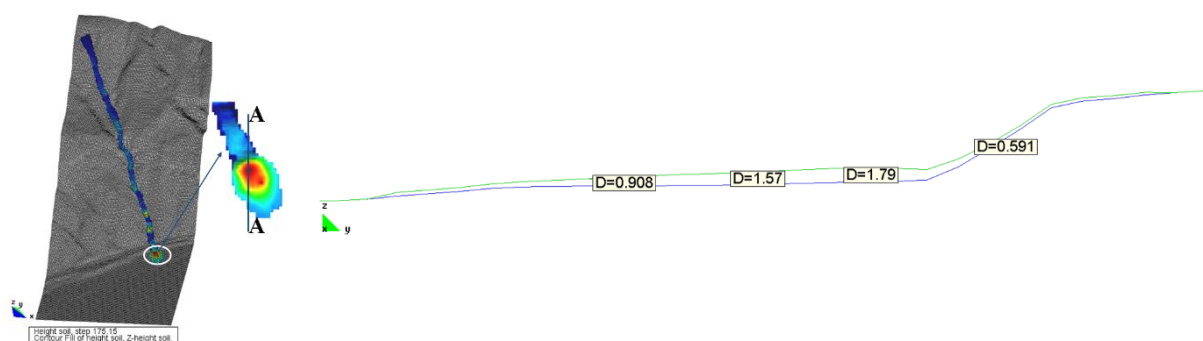
The maximum height and velocity of the flow at the end of the path and the final volume are listed in table 5.

**Table 5** – Simulation results.

Height_soil <sub>max</sub> [m]	$v_{\max}$ [m/s]	$V_{\text{final}}$ [m <sup>3</sup> ]
1,83	10,05	5422,226

The final volume is four times the initial one according to the values of the real events of the area. In figure 11 is represented the landslide contour along AA section in the accumulation zone.

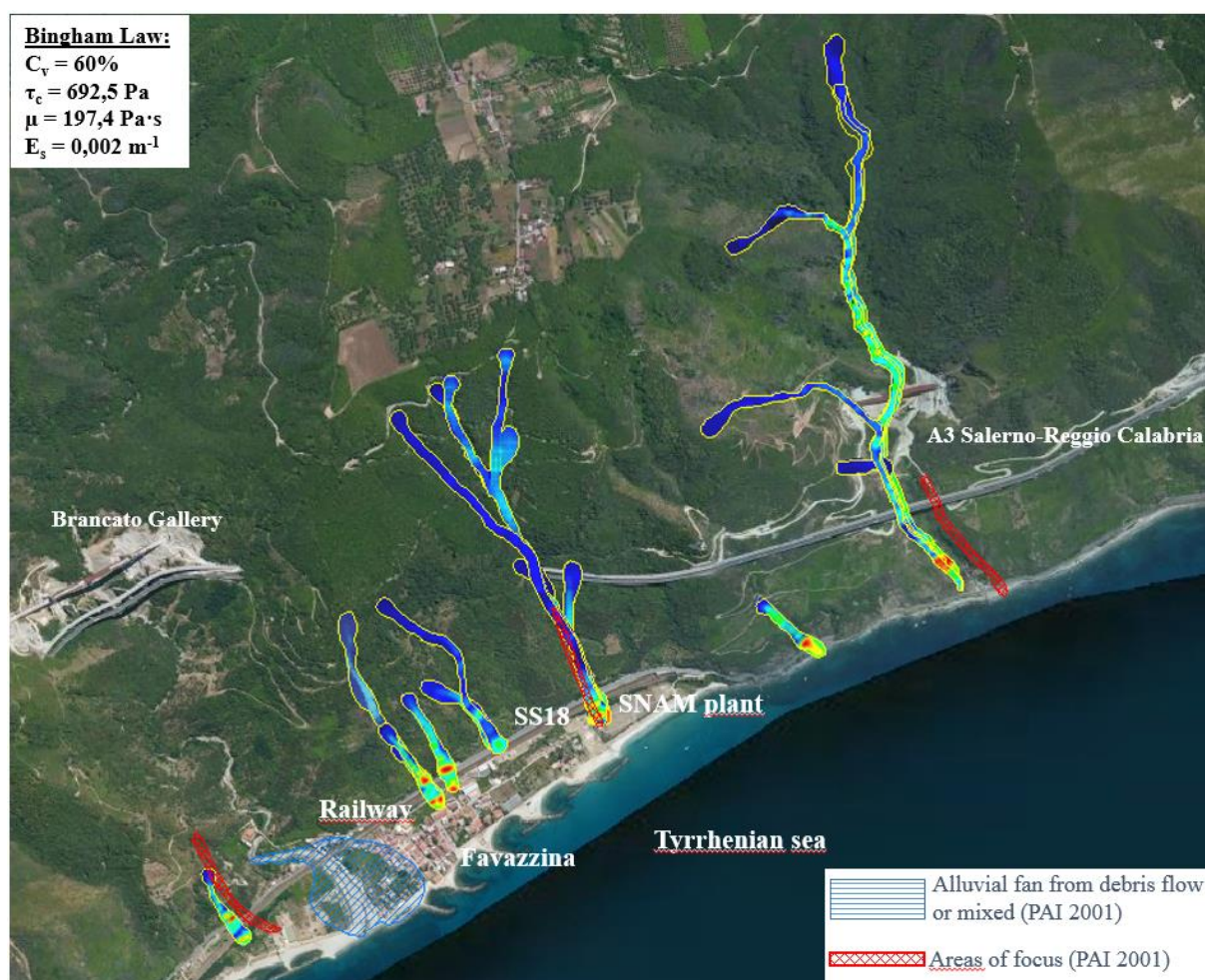




**Figure 11** – Height soil values along AA section.

Figure 11 shows the thicknesses ( $D$ ) of the flow-like landslide along the section AA in the accumulation area. These values are important to identify appropriate mitigation measures.

The previous numerical analysis was performed on more hypothetical detachment points allowing so the drafting of a susceptibility map of the whole studied area, represented in Figure 12.



**Figure 12** – Susceptibility map of the Favazzina area.

The achieved results demonstrate that, for the study area, a viscous rheology with the parameters shown at the top right of the figure and in table 4 is adequate to simulate this type of landslide.

#### 4. Conclusions

The analysis of the events classified as flow-like landslides occurred in the southern Italy has been carried out; in particular the area between Scilla and Favazzina has been chosen. Two susceptibility descriptors have been used in order to characterize these events, natural slopes and lithological features of the detachment zones of the landslide mass. The investigation has shown the largest number of the events has been occurred in the slope ranges of 38°-40° and 41°-43°. Lithology mainly affected by the flowlike landslides has been paragneiss, gneiss and biotitic schists, which covered almost all the examined area.

The results achieved have allowed to individuate hypothetical detachment zones, in the study area, with slopes and lithological features similar to those of real events. In this case, the most involved slopes have been 41°-43°, whereas lithology more affected has been paragneiss as previously checked. In order to evaluate the runout distances and the velocity of the landslide, numerical simulations have been carried out to show the susceptibility of the elements at risk. A depth-integrated, coupled SPH method has been used, considering a Bingham viscous law as rheological model, taking into account the erosion phenomenon. The achieved results have demonstrated the capability of the model to simulate the propagation phase and have allowed to obtain essential data to design appropriate prevention and mitigation measures for the elements at risk.

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#### 5. References

- [1] Hungr O, Leroueil S and Picarelli L 2014 The Varnes classification of landslide types, an update *Landslides* **11** 167-194
- [2] Varnes DJ 1954 Landslide types and processes *Landslides and engineering practice, special report 28*, ed E B Eckel (Washington, DC: Highway research board. National Academy of Sciences) pp. 20-47
- [3] Varnes DJ 1978 Slope movement types and processes. In: Schuster RL, Krizek RJ (eds) *Landslides, analysis and control, special report 176*: Transportation research board, National Academy of Sciences, Washington, DC., pp. 11-33
- [4] Cruden DM, Varnes DJ 1996 Landslide types and processes. In: Turner AK, Schuster RL (eds) *Landslides investigation and mitigation*. Transportation research board, US National Research Council. Special Report 247, Washington, DC, Chapter 3, pp. 36-75
- [5] Jakob M and Hungr O 2005 Introduction. In: Hungr O, Jakob M (eds) *Debris-flow hazards and related phenomena*. Springer-Praxis, Berlin, pp 1-7
- [6] Gullà G, Mandaglio M C, Moraci N and Sorriso-Valvo M 2004 Definizione degli elementi generali di dei modelli geotecnici per l'analisi delle instabilità superficiali per scorrimento-colata in Calabria jonica. *Atti del XXII Convegno Nazionale di Geotecnica, Palermo 22-24 settembre 2004*, 127-134.
- [7] Gullà G, Mandaglio M C, Moraci N 2006 - Effect of weathering on the compressibility and shear strength of a natural clay. *Canadian Geotechnical Journal* **43**: 618-625
- [8] Gullà G., Mandaglio M.C., Moraci N. 2005 - Influence of degradation cycles on the mechanical characteristics of natural clays. *Proceedings of 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka (Japan), 12-16 September 2005*: 2521-2524.
- [9] Borrelli L., Giofrè D., Gullà G., Moraci N. 2012 - Susceptibility to shallow and rapid landslides in ground alteration: A possible contribution of propagation modeling - Suscettibilità alle frane superficiali e veloci in terreni di alterazione: un possibile contributo della modellazione della propagazione. *Rend. Online Soc. Geol. It., Vol. 21 (2012), pp. 534-536, Società Geologica Italiana, Roma 2012.*



- [10] Bonavina M, Bozzano F, Martino S, Pellegrino A, Prestininzi A and Scandurra R 2005 Le colate di fango e detrito lungo il versante costiero tra Bagnara Calabria e Scilla (Reggio Calabria): valutazioni di suscettibilità. *Giornale di Geologia Applicata* **2** 65-74
- [11] Liu G R and Liu M B 2003 Smoothed Particle Hydrodynamics: A Meshfree Particle Method World Scientific (ed)
- [12] Lucy L B 1977 Numerical approach to testing the fission hypothesis, *Astronomical Journal*, **82**:1013-1024
- [13] Gingold R and Monaghan J J 1977 Smoothed Particle Hydrodynamics: Theory and Application to Non-spherical stars, *Monthly Notices of the Royal Astronomical Society*, **181**:375-389
- [14] Pastor M, Haddad B, Sorbino G, Cuomo S and Drempetic V 2009 A depth-integrated, coupled SPH model for flow-like landslides and related phenomena, *Int. J. Numer. Anal. Meth. Geomech.*, **33**:143–172
- [15] Gioffre' D 2005 Modellazione numerica dei fenomeni di frane di colata. PhD Thesis in Geotechnical Engineering (XVII cycle) "Mediterranea" University of Reggio Calabria
- [16] Hungr O 1995 A model for the runout analysis of rapid flow slides, debris flows and avalanches. *Canadian Geotechnical Journal*, **32**, 610-623