Spatial and temporal occurrence of rainfall-induced shallow landslides of flow type: A case of Sarno-Quindici, Italy

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Abstract

Rainfall-induced shallow landslides of flow type provide unstable masses which often travel long run-out distances with high velocities, thus posing a high societal risk when they affect large areas. Therefore, analysis of their spatial and temporal occurrence is relevant to landslide hazard assessment as the first step in the risk analysis. In order to address this issue, this paper outlines a multidisciplinary procedure that is applied to the May 1998 Sarno-Quindici landslides (southern Italy), whose spatial and temporal occurrence is not satisfactorily addressed in current literature. The spatial occurrence of the landslides is analysed using heuristic models for both the source and propagation areas. The temporal occurrence of the landslides is firstly compiled and then related to the cumulated rainfall, stratigraphy and hydraulic boundary conditions. Finally, the spatial and temporal occurrence of the main landslide triggering mechanism is modelled over the whole affected area by analysing the groundwater regime and slope stability conditions. The obtained results show that the spatial and temporal occurrence is strongly related to stratigraphy and hydraulic boundary conditions at both the slope and massif scales. They also highlight a suitable procedure for assessing the spatial and temporal occurrence of complex landslides over large areas.

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1. Introduction

Rainfall-induced shallow landslides of flow type (Hungr et al., 2001) can travel long run-out distances (hundreds of meters), often with high velocities on the order of m s⁻¹. When they occur over a large area, they may pose a high societal risk (Cascini et al., 2008a) as testified by several examples all over the world (Fuchu et al., 1999; Wang et al., 2002; Capra et al., 2003; Lacerda, 2004; Take et al., 2004). Understanding these destructive phenomena through the analysis of the relationships among their spatial/temporal occurrences and the predisposing/trIGGERING factors is important in order to reduce their negative consequences.

In literature, the distribution of landslide source areas is analysed using different models commonly implemented on GIS platforms (van Westen, 2004). The so-called geological models relate the distribution of landslide source areas to combinations of spatial variables such as slope angle and thickness of deposits using either heuristic (Dai and Lee, 2002) or statistical methods (Dai and Lee, 2002; Corominas et al., 2003). More advanced models simulate the hydrological response of hillslopes and evaluate their stability conditions. Among these, physically based models (Dietrich and Montgomery, 1998; Godt et al., 2008) analyse large areas using the simplified scheme of infinite slope, while geomechanical models (Cascini et al., 2010) refer to single slope sections and more detailed stratigraphies. Landslide propagation areas are mainly analysed through mathematical models which simulate landslide propagation stages (Pastor et al., 2009) and empirical models which relate the run-out distance to topography and the volume of unstable mass (Corominas, 1996). In contrast, the temporal occurrence of shallow landslides is addressed independently. Either black-box models are used which relate the failure onset to the amount of cumulative rainfall (Caine, 1980) or hydrological models which simulate the effects of rainfall through analytical relationships (Sirangelo and Braca, 2004).

The correlation between the spatial and temporal occurrences of shallow landslides over large areas can be analysed using physically based models. However, the success and error of these models strictly depend on both the characteristics of the landslide source areas and triggering mechanisms (Soribino et al., 2009). As a consequence, a general approach is not yet available in current scientific literature to tackle this issue. This paper contributes to the topic investigating a relevant case (May 1998 Sarno-Quindici event, southern Italy) for which an advanced geotechnical dataset is available.

2. Studied event and methods

2.1. The event

The May 1998 event (Cascini, 2004) is among the most catastrophic recent natural disaster in the Campania region which is one of the most landslide-prone areas in Europe (Cascini et al., 2008a).
This event was characterised by tens of flow-type landslides over a 60 km² massif (Cascini et al., 2005, 2008b; Guadagno et al., 2005) (Fig. 1). The affected area consists of shallow (depth < 5) unsaturated pyroclastic air-fall deposits, originating from the explosive activity of the Somma-Vesuvius volcanic apparatus (Cascini et al., 2008a). The bedrock below is a fractured and karsified carbonate massif, characterised by a suspended groundwater flow system in its upper part and springs at different altitudes along the hillslopes (Cascini et al., 2008b). The hillslopes contain three typical geomorphological units: zero order basins (zobs), open slopes and flanks of valley (Cascini et al., 2008b). Zero order basins are colluvial hollows with a concave bedrock profile characterised by a maximum depth in the

![Fig. 1. The Sarno-Quindici study area affected by the May 1998 flow-type landslides.](image1)

![Fig. 2. Three types of landslide source areas (M1, M2 and M3). a) schematic illustration of the three types. 1: bedrock, 2: pyroclastic deposits, 3: track, 4: spring from bedrock. b) distribution of the three types and geomorphological units affected (1) and not affected (2) by the May 1998 landslides.](image2)
central part. The open slopes have a nearly constant slope angle and depth of the pyroclastic deposits. The flanks of valley are hillslopes with a channel at the lower part.

Concerning the spatial occurrence of the May 1998 landslides, Cascini et al. (2008b) note that failures occurred in all of the three geomorphological units, with the corresponding landslide source areas being referred to as M1, M2 and M3, respectively. M1 inside the zobs is characterised by elongated planforms. M2 on open slopes has triangular planforms. M3 on the flanks of valley show compound landforms.

The triggering mechanisms of the landslides in the M1, M2 and M3 source areas are also labelled as M1, M2 and M3, respectively. The triggering mechanism M1 is related to rainwater infiltrating the ground surface and temporary springs from the bedrock. The triggering mechanism M2 is caused by springs from karst conduits and/or impact of small landslides occurred at the top of bedrock scarps. The triggering mechanism M3 is related to rainfall infiltration and concentration of runoff water in particular zones close to mountain roads or tracks. All these mechanisms were analysed by Cascini et al. (2008b,c,d) for the geomechanical modelling of the failure stage. It should be stressed that the different landslide triggering mechanisms in different geomorphological units reduce the ability of physically based models as shown by Sorbino et al. (2009). Similar difficulties arise when geological and geomechanical models are used.

For the propagation areas, Budetta and de Riso (2004) indicate that the May 1998 landslides had a higher mobility than analogous slope instability phenomena in other areas of the Campania region (i.e. Sorrento Peninsula). The mobility of these landslides is also addressed by Pareschi et al. (2002) through geomorphological analyses as well as Revellino et al. (2004) and Pastor et al. (2009) through numerical modelling. However, the relationship between the run-out distance and triggering mechanisms has not been discussed in the current scientific literature.

Relative to the temporal occurrence, Rossi and Chirico (1998) and De Vita (2000) relate the onset of the May 1998 landslides to both critical 2-day as well as antecedent cumulative rainfall values. Sirangelo and Braca (2004) propose a hydrological model to explain the temporal occurrence of the May 1998 landslides that are analysed as a single event, while Cascini et al. (2003) demonstrate that multiple failures occurred inside a single landslide source area over a time period of about 10 h. These contributions, however, do not discuss the temporal occurrence of these landslides in the whole affected area.

2.2. Adopted procedure

This paper jointly analyses the spatial and temporal occurrences of landslides, considering the main geological and geotechnical aspects at both the slope and massif scales. With this aim in mind, the adopted procedure addresses four main questions: i) Is it possible to discriminate between geomorphological units affected and not affected by failures, on the basis of their features before the event? ii) Is the landslide run-out distance related to the location and features of the source areas? iii) Is

| Table 1 | Morphometry of the main geomorphological units. |
|---|---|---|
| Landforms | Morphometry | Pyroclastic deposits |
| | Slope angle (°) | Length (m) | Width (m) | Area (m²) | Depth (m) | Volume (m³) |
| | 15th perc. | Mean | 85th perc. | Mean | Mean | Min | Max | Min | Max | Min | Max |
| Zero order basin | 29 | 32 | 35 | 295 | 111 | 5413 | 69,889 | 2 | 4.5 | 10,826 | 314,500 |
| Open slope | 20 | 28 | 34 | 357 | 519 | 32,586 | 411,265 | 1 | 4.5 | 32,586 | 1,850,696 |
| Flank of valley | 30 | 34 | 39 | 109 | 603 | 1203 | 169,432 | 1 | 4.5 | 1203 | 762,444 |

Fig. 3. Spatial distribution of pyroclastic soils and typical stratigraphy types (1–4) of the pyroclastic air-fall deposits for each sector of the massif.
the temporal landslide occurrence related to the predisposing and triggering factors? iv) Are the spatial and temporal occurrences of the landslides independent?

In order to answer these questions, heuristic analyses are initially carried out. In particular, the onset of landslides in their source areas is analysed in relation to the morphometric and stratigraphic characteristics of the main geomorphological units before failure. Subsequently, the run-out distance is related to the location of the source areas and triggering mechanisms. The failure time sequence is also investigated in relation to the landslide triggering mechanisms. Finally, the spatial and temporal occurrences of the landslides are concurrently analysed through the geomechanical modelling of their failure stage in order to evaluate the temporal variations of the slope stability conditions over the massif.

These analyses are carried out using an extensive geotechnical dataset obtained from current literature (U.O. 2.38, 1998; Sorbino and Foresta, 2002; Crosta and Dal Negro, 2003; Picarelli et al., 2004; Bilotta et al., 2005; Cascini et al., 2006). Details on the geological setting can be found in Cascini et al. (2008b), while details on the geotechnical properties of the involved pyroclastic soils are provided by Bilotta et al. (2005), who identified three main lithotypes: pumice soils essentially constituted by sands and gravels, coarser superficial ashy silty sands (class B), and finer deep ashy sandy silts (class A).

3. Analysis of landslide spatial occurrence

3.1. Failure onset

The landslide spatial occurrence was investigated in relation to the three main geomorphological units (Fig. 2). Among the 178 geomorphological units shown in Fig. 2, only 48 were affected by slope failures during the May 1998 event, of which 26 inside zobs (out of a total of 79; 33%), three on open slopes (out of 23; 13%) and 19 on flanks of valley (out of 76; 25%).

Table 1 shows that the slope angle is the highest for the flanks of valley and the smallest for open slopes. In contrast, the areal extension is the largest for open slopes and smallest for zobs. The thickness of the pyroclastic deposits is the largest in the zobs and the smallest on flanks of valley, but the volume of the pyroclastic deposits (evaluated by simply assuming a rectangular transversal section) is the largest for open slopes and smallest for flanks of valley.

During the May 1998 event, zobs and flanks of valley were mostly affected by the landslides. This observation can be related to the thickest pyroclastic deposits inside the zobs and the highest slope angles on the flanks of valley. However, the zobs and flanks of valley affected by the failures have a wide range of slope angles, while only the steepest open slopes experienced failures in most cases. Consequently, it is impossible

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**Table 2**

<table>
<thead>
<tr>
<th>Sector of the massif</th>
<th>Stratigraphy (type)</th>
<th>Geomorphological units (number)</th>
<th>Geomorphological units affected by failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracigliano-Siano</td>
<td>1 or 2</td>
<td>45</td>
<td>33</td>
</tr>
<tr>
<td>Quindici</td>
<td>3 or 4</td>
<td>36</td>
<td>44</td>
</tr>
<tr>
<td>Sarno</td>
<td>5 or 6</td>
<td>97</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sector of the massif</th>
<th>Stratigraphy (type)</th>
<th>Geomorphological units (number)</th>
<th>Geomorphological units affected by failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zob</td>
<td>2</td>
<td>12</td>
<td>33%</td>
</tr>
<tr>
<td>Open slope</td>
<td>3</td>
<td>15</td>
<td>25%</td>
</tr>
<tr>
<td>Flank of valley</td>
<td>4</td>
<td>24</td>
<td>38%</td>
</tr>
</tbody>
</table>

**Fig. 4.** Travel paths of the landslides selected for the analysis of the run-out distance, I) influenced and II) not influenced by anthropogenic structures at the toe of the massif.
to strictly relate the landslides spatial occurrence to the morphometry of the geomorphological units, as also highlighted by Guadagno et al. (2005) as well as Di Crescenzo and Santo (2005). Therefore, other aspects must be taken into account such as the stratigraphy of the slope deposits. The latter is thus discussed using 325 stratigraphical profiles, as well as the porosity values $n$ and specific gravity $G_s$ of 111 laboratory specimens of ashy soils (data from U.O. 2.38, 1998). The spatial distribution of ashy (A and B) and pumice soils is shown in Fig. 3, where the main sectors of the massif show four stratigraphic types: i) stratigraphy 1 with only ashy B soil near the ground surface; ii) stratigraphy 2 with ashy B soil above ashy A soil on the bedrock; iii) stratigraphy 3 with ashy B soil, a pumice layer and ashy A soil; iv) stratigraphy 4 similar to stratigraphy 3 but with two to four pumice layers.

We observed that: i) slope failures mainly involved ashy B and pumice soils and, to a minor extent, ashy A soil; and ii) the highest percentage (44%) of geomorphological units affected by the failures occurred in the sector of Quindici (Table 2).

Further insights on this topic can be obtained by separately analysing the different geomorphological units in relation to their stratigraphy (Table 2), and considering the triggering factors in the analysis. For example, regarding zobs with all the stratigraphical settings (1-4), more pumice soil layers may correspond to decreased failures. This could be essentially due to triggering mechanism M1, i.e. rainfall infiltrating the ground surface and springs from the bedrock.

In this case, continuous pumice soil layers could improve the slope stability conditions. However, similar results cannot be found for the other geomorphological units where mechanisms M2 and M3 occurred, meaning that other factors should be investigated.

### 3.2. Run-out distance

Landslide spatial occurrence was further analysed in relation to the height of fall ($H$) and run-out distance ($L$). $H$ and $L$ were computed between the uppermost landslide source area and the lowest deposition area; $L$ was measured along the landslide propagation path (Fig. 4).

The obtained results (Fig. 5a) highlight that anthropogenic structures such as paved roads and channels located at the toe of hill slopes, significantly increased the landslide run-out. In particular, the reach angle $\alpha$ (i.e. the arctangent of the ratio of $H$ to $L$) is significantly lower for the landslides influenced by the anthropogenic structures (Fig. 5a). $H$ and $L$ are well interpreted by linear relationships as indicated by previous studies (Pareschi et al., 2002; Budetta and de Riso, 2004).

Further insights into the run-out distances were obtained by subdividing the dataset in terms of the position and type of the landslide source areas. For instance, in the northwest sector of the massif (i.e. Quindici and Bracigliano) the landslides had a similar mobility (Fig. 5b), but different from those in the southern sectors of the massif (i.e. Sarno and Siano), where the landslides exhibited longer travel distances and...
lower reach angles. Moreover, the propagation pattern of single
landslides and that of multiple landslides (i.e. landslides which joined
along the propagation path; Fig. 4) are also different, with the latter
having longer travel distances and lower reach angles (Fig. 5c).

Concerning single landslides, $L$ and $H$ show a good correlation for
M1 and M2, but not for M3 (Fig. 5d). In particular, the lowest reach
angles were obtained for M1 and comparable travel distances are
observed for M1 and M2. In conclusion, the run-out distance of the
landslides depends on both the location (i.e. the sector of massif) as
well as the features of the landslide source areas (M1 to M3).

4. Analysis of landslides temporal occurrence

4.1. Reconstruction of failures time sequence

The temporal occurrence of the May 1998 landslides was recon-
structed using the available eyewitnesses who provided the arrival time
of the failed masses at the toe of the massif (Fig. 6). These data highlight
that the landslides firstly affected the sectors of Quindici (from 5th May
11 a.m.) and Bracigliano (2 p.m.), then Siano and Sarno-Lavorate (4 p.m.)
and finally Sarno-Episcopio (8 p.m.). Moreover, inside the sectors of
Quindici, Bracigliano and Siano, the landslides occurred before 5th May
9 p.m. while in the other sectors the landslides did not occur until 12 p.m.

Due to the high velocities of the propagating masses that travelled
the paths within a few minutes, the arrival time at the end of the
travel paths nearly corresponds to the failure time in the landslide
source areas (Fig. 6). Therefore, it is possible to say that: i) 11 M3
source areas experienced landslides in about 11 h from 5th May 11 a.
.m. (except for a landslide occurring after 10 p.m.), ii) 33 M1 areas did
over a longer time period (13 h after 11 a.m.), and iii) 11 M2 areas did
in a shorter time period (8 h after 4 p.m.).

4.2. Analysis of the failure time sequence

The failure time sequence was investigated by analysing the
amount of rainfall between 4th May and failure, since rainfall was a
triggering factor for all the mechanisms M1, M2 and M3 (Cascini et
al., 2008a,b,c). The analysis was based on twice the rainfall data
recorded at the S. Pietro rain gauge (Cascini et al., 2003) located at
215 m a.s.l. and 10 km away from the Pizzo d’Alvano massif. The results show that the landslides in
Fig. 6 were triggered by rainfall values of 156–210 mm for M3, 156–248 mm for M1 and
192–248 mm for M2.

The failure time sequence described in Section 4.1 indicates that a
strict correspondence between the rainfall amount and the failure
onset does not exist. Consequently, other triggering factors must be
considered in order to explain the sequence. In particular, the earliest
failure occurrence and low rainfall values for M3 could be explained
by the topography that allows the rapid concentration of rain water
at the bends of the tracks. Conversely, the higher rainfall amount
required for triggering failures in M2 areas could be explained by
water infiltration into karst conduits.

More insights are provided for M1 areas (Fig. 7). For instance, the
earlier landslide occurrence in the Quindici sector rather than in Sarno
could be related to the differences in the stratigraphy of the
pyroclastic deposits as well as the bedding of the bedrock layers
which affects the springs from the bedrock, earlier acting in Quindici
(Cascini et al., 2008b). Stratigraphy could also explain the later
occurrence of failures in Sarno-Episcopio compared to Sarno-
Lavorate. These inferences should be confirmed through the geome-
chanical modelling of the failures.

5. Geomechanical modelling

Following the procedure described in Section 2.2, the failure
stage of the triggering mechanism M1 was analysed by using
the simplest approach of Cascini et al. (2010). This approach is
based on the following steps: i) computation of pore water
pressures with the aid of a transient uncoupled analysis of the
groundwater regime, and ii) slope stability analyses using limit
equilibrium methods.
5.1. Slope schemes and soil properties

The slope schemes for the modelling were obtained from the typical stratigraphical settings outlined in Section 3.1. For each sector of the massif, typical stratigraphies and slope angles were considered while different depths of the pyroclastic deposits were assumed (Fig. 8).

The physical and mechanical properties were taken from current literature. The volumetric water content and hydraulic conductivity curves for ashy A and B soils, obtained through the suction controlled oedometer, volumetric pressure plate extractor and Richards pressure plate, were discussed by Sorbino and Foresta (2002), while empirical relationships are available for pumice soils (Sorbino and Foresta, 2002; Bilotta et al., 2005). On the other hand, the shear strength and compressibility properties of ashy soils in both saturated and unsaturated conditions were also discussed by Bilotta et al. (2005, 2008). The properties used are summarised in Fig. 9 and Table 3. A full parametric analysis was carried out by changing the soil shear strength parameters.

5.2. Groundwater modelling

We initially simulated pore water pressure changes between 1st January and 5th May, 1998. A saturated–unsaturated transient groundwater model was adopted from Richards (1931):

\[
\frac{\partial}{\partial x} (k_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial h}{\partial y}) = m_w \gamma_w \frac{\partial h}{\partial t}
\]

where \( k_x \) and \( k_y \) are the hydraulic conductivities in the x and y directions, \( m_w \) is the suction parameter, \( \gamma_w \) is the unit weight of water, and \( \frac{\partial h}{\partial t} \) is the time derivative of the hydraulic head h.
where $m_w$ is the coefficient of volumetric water changes with respect to the change in negative pore pressure, and it is equal to the slope of the soil–water characteristic curve; $h$ is the total head; $k_x$ and $k_y$ are the soil conductivity coefficients in $x$ and $y$ directions; $\gamma_w$ is the unit weight of water; and $t$ is time.

The commercial finite element code SEEP/W (Geoslope, 2005) was applied to a finite element mesh with 3500 quadrilateral elements with lengths and heights respectively smaller than 1.43 and 0.18 m and the soil parameter values in Table 3. As a boundary condition at the ground surface, a flux condition was assumed equal to daily rainfall intensity recorded at the toe of the hillslopes between the 1st of January and 3rd of May 1998. For the last 2 days (4th–5th May), the hourly rainfall intensities mentioned in Section 4.2 were assumed. The evapo-transpiration phenomena were neglected because Sorbino (2005) demonstrates that such phenomena do not significantly affect the suction regime during Spring. As a boundary condition at the bedrock contact, an impervious condition is assumed over the slope section except where a spring from the bedrock has been operating with a flux of $8.57 \times 10^{-3}$ m$^3$ s$^{-1}$ since 3rd of May 1998 (Cascini et al., 2003). As an initial condition, a uniform distribution of suction equal

Table 3

<table>
<thead>
<tr>
<th></th>
<th>$\gamma_d$ (kN m$^{-3}$)</th>
<th>$\gamma_{sat}$ (kN m$^{-3}$)</th>
<th>$n$ (–)</th>
<th>$k_x$ (m s$^{-1}$)</th>
<th>$c'$ (kPa)</th>
<th>$\phi'$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashy soils (class A)</td>
<td>9.1</td>
<td>15.7</td>
<td>0.66</td>
<td>$10^{-6}$</td>
<td>5–15</td>
<td>32–35</td>
</tr>
<tr>
<td>Pumice</td>
<td>6.2</td>
<td>13.1</td>
<td>0.69</td>
<td>$10^{-4}$</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>Ashy soils (class B)</td>
<td>7.3</td>
<td>13.1</td>
<td>0.58</td>
<td>$10^{-5}$</td>
<td>0–5</td>
<td>36–41</td>
</tr>
</tbody>
</table>

Fig. 9. Geotechnical properties of pyroclastic soils. a) grain size distribution. b) saturated shear strength envelopes. c–d) peak shear strength of ashy A and B soils versus net vertical stress for some ranges of saturation degree ($S_{rf}$) (after Bilotta et al., 2005).

Fig. 10. Typical groundwater regime for different slope schemes after 12 h.
to 10 kPa is assumed all over the slope section based on Cascini et al. (2003, 2005).

The obtained results show that the simulated pore water pressure regime significantly differs for the assumed slope schemes (Fig. 10), especially in the zone with the spring. The highest pore water pressures were simulated for the schemes QU, SL and SE (i.e. where B and A soils are present) and the lowest values correspond to the schemes BR and SI (i.e. containing only B soils). These differences can be profitably interpreted based on the concept of trasmissivity

\[ T = \sum \frac{k_i \cdot b_i}{s} \]  

where \( i \) represents the number of soil layer, \( k_i \) is the saturated hydraulic conductivity and \( b_i \) is the depth of each soil layer.

Cascini et al. (2003) demonstrate that \( T \) is a simple but efficient parameter to interpret slope responses to rainfall infiltration which strongly affects both the spatial and temporal occurrences of slope failures.

For the assumed slope schemes of Fig. 8, \( T \) varies from \( 2.97 \times 10^{-5} \) to \( 8.37 \times 10^{-5} \) m²s⁻¹, corresponding to the range assumed by Cascini et al. (2003, 2005) except the schemes SI2, BR2 and QU2. For these schemes, the simulated high pore water pressures are associated with the low values of \( T \) and vice versa (Fig. 11).

5.3. Slope stability analysis

In relation to the computed pore pressures, slope stability analyses were carried out to simulate failure conditions mainly where the spring from the bedrock is located. These local failures can induce multiple retrogressive landslides which can entirely mobilize the pyroclastic deposits of zero order basins (Cascini et al., 2003, 2005).

The slope stability conditions were evaluated through the limit equilibrium methods proposed by Janbu (1954) as well as Morgenstern and Price (1965) by using the commercial SLOPE/W code (Geoslope, 2005). A rigid-perfectly plastic constitutive model was used for the involved soils referring, in both saturated and unsaturated conditions, to the extended Mohr–Coulomb failure criterion proposed by Fredlund et al. (1978). A parametric analysis was carried out for the aforementioned slope schemes using the soil mechanical properties in Table 3.

The slope stability conditions were initially computed based on the pore water pressures simulated for the beginning of 4th May 1998. For the schemes SL2, SL4.5, SE2, SE4.5 and QU4.5, the factor of safety (\( FS \)) is higher than 1 only when \( c' \) is not null for ashy A soils. If \( c' \) is assumed to be 15 kPa, \( FS \) is always higher than 1 irrespective of \( \phi' \) for the ashy B soils. For the schemes SI4.5 and BR4.5, \( FS \) higher than 1 is simulated only when \( \phi' \) is higher than 37° for the ashy B soils. For the remaining slope schemes SI2, BR2 and QU2, \( FS \) is lower than unity, irrespective of the soil mechanical properties, which is inconsistent with the in-situ evidence. These results can be explained by the values of \( T \) assumed for these schemes, which are lower than those used by Cascini et al. (2003, 2005) to satisfactorily back-analyse the 1998 landslides.

Focusing on the realistic slope schemes (QU4.5, SL2, SI4.5, SE2, SE4.5, SI4.5, and BR4.5), the slope stability conditions were evaluated during the time period 4-5 May 1998, at each time step (i.e. hourly),

Fig. 11. Trasmissivity of different slope sections used for modelling.

Fig. 12. Simulated unstable volumes for the slope schemes of Fig. 8.
Heuristic or statistical methods are generally suggested to evaluate the spatial occurrence of landslides, while a joint evaluation of the spatial and temporal occurrence can be carried out through physically based models. However, the latter models have several limitations when different triggering mechanisms occur in a study area. Moreover, without heuristic analyses, the geological context of landslides is not sufficiently analysed and misleading results may be obtained. This paper has proposed a joint use of the different approaches and has dealt with one of the most catastrophic landslide events in the Campania Region (Southern Italy) which has a very high landslide risk.

Heuristic analyses allowed us to characterise the landslide source areas but they cannot explain the spatial occurrence of the landslides if only the predisposing factors are considered. i.e. morphometry and thickness/.stratigraphy of slope deposits. Conversely, satisfactory results were obtained when the triggering mechanisms were taken into account. The triggering factors play an important role at different scales (e.g. rainfall at massif scale and local hydraulic boundary conditions at slope scale). They also determine the time failure sequence. Moreover, the location and features of the source areas significantly affect the run-out distance of the landslides. Finally, focusing on a triggering mechanism, geomechanical analyses outline that a low value of transmissivity of soil deposits is an important predisposing factor, and the stratigraphy determines the volume and temporal occurrence of the failures.

The obtained results highlight how to assess the spatial and temporal occurrence of shallow landslides in a large area. Heuristic analyses can be used to identify the landslide source areas, outline the predisposing and triggering factors of landslides as well as assess the landslides spatial–temporal occurrence. When satisfactory results are not obtained for the last two points, geomechanical analyses can be carried out to correctly capture the most relevant factors. In particular, parametric analyses can outline the role of soil properties, stratigraphy and hydraulic boundary conditions that affect the groundwater regime and, consequently, the spatial and temporal occurrence of the landslides.

6. Conclusions

The assessment of the spatial and temporal occurrence of rainfall-induced shallow landslides of flow type is important because of the high risk posed by long run-out distances and high velocities of the unstable masses. It is, however, complex when large areas are simultaneously affected because of the heterogeneous morphological units and stratigraphy of the landslide source areas. In order to tackle this problem, the use of heuristic, statistical or physically based approaches has been proposed in current literature. Heuristic or statistical methods are generally suggested to evaluate the spatial occurrence of landslides, while a joint evaluation of the spatial and temporal occurrence can be carried out through physically based models. However, the latter models have several limitations when different triggering mechanisms occur in a study area. Moreover, without heuristic analyses, the geological context of landslides is not sufficiently analysed and misleading results may be obtained. This paper has proposed a joint use of the different approaches and has dealt with one of the most catastrophic landslide events in the Campania Region (Southern Italy) which has a very high landslide risk.

Heuristic analyses allowed us to characterise the landslide source areas but they cannot explain the spatial occurrence of the landslides if only the predisposing factors are considered. i.e. morphometry and thickness/stratigraphy of slope deposits. Conversely, satisfactory results were obtained when the triggering mechanisms were taken into account. The triggering factors play an important role at different scales (e.g. rainfall at massif scale and local hydraulic boundary conditions at slope scale). They also determine the time failure sequence. Moreover, the location and features of the source areas significantly affect the run-out distance of the landslides. Finally, focusing on a triggering mechanism, geomechanical analyses outline that a low value of transmissivity of soil deposits is an important predisposing factor, and the stratigraphy determines the volume and temporal occurrence of the failures.

The obtained results highlight how to assess the spatial and temporal occurrence of shallow landslides in a large area. Heuristic analyses can be used to identify the landslide source areas, outline the predisposing and triggering factors of landslides as well as assess the landslides spatial–temporal occurrence. When satisfactory results are not obtained for the last two points, geomechanical analyses can be carried out to correctly capture the most relevant factors. In particular, parametric analyses can outline the role of soil properties, stratigraphy and hydraulic boundary conditions that affect the groundwater regime and, consequently, the spatial and temporal occurrence of the landslides.

References


