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A SIMPLIFIED PHYSICALLY-BASED APPROACH FOR THE ASSESSMENT OF HAZARD RELATED TO SHALLOW LANDSLIDES IN SOUTHERN PIEDMONT (ITALY)

ABSTRACT: FONTE N. & MASCIOCCO L., *A simplified physically-based approach for the assessment of hazard related to shallow landslides in Southern Piedmont (Italy)*. (IT ISSN 0391-9838, 2009).

After a critical analysis on the main methods of evaluation of hazard related to shallow landslide, a simplified approach is proposed which takes into account rainfall infiltration in the soil and its influence on slope stability. For the infiltration analysis, the model uses the Green-Ampt method that considers the downward advancement of a saturation front from the ground surface as a consequence of a given rainfall. The thickness of saturated soil is used as input information for the stability analysis according to the indefinite slope method. The utilization of the Safety Factor equation allows to relate the input rainfall data with the landslide triggering through the thickness of saturated soil, assuming very-low values for cohesion and friction angle.

The goal of the proposed approach is to investigate the triggering conditions for shallow landslides in relation to specific rainfalls whose frequency is computable, allowing for the drawing up of landslide hazard maps.

The approach has been tested in some areas of Monferrato and Langhe Hills (Southern Piedmont, north-western Italy), valuable vineyard territories characterized by a high frequency of shallow landslides, which are commonly triggered when a drastic decrease of friction angle and cohesion occurs. Values of 20° and 0.5 kN/m^2, for the friction angle and cohesion respectively, in conditions of total saturation, seem to give good results in the comparison between simulated and observed landslides. At present, other calibration tests are being carried out in the Alto Monferrato area.

KEY WORDS: Shallow landslides, Landslide hazard, Land planning, Southern Piedmont (Italy).

RIASSUNTO: FONTE N. & MASCIOCCO L., *Metodo semplificato fisicamente basato per lo studio della pericolosità da frane superficiali nel Piemonte meridionale*. (IT ISSN 0391-9838, 2009).

In seguito ad un'analisi critica sui principali lavori riguardanti le frane superficiali, in questo articolo viene proposto un modello semplificato per lo studio della pericolosità da frane superficiali. Il modello prende in considerazione sia l'infiltrazione della pioggia nel suolo sia la sua influenza sulla stabilità del pendio. Per l'analisi dell'infiltrazione il modello utilizza il metodo di Green & Ampt che considera l'avanzamento, dalla superficie del versante verso il basso, di un fronte di saturazione in seguito a una pioggia di progetto. Il valore di profondità del suolo saturo (h) viene utilizzato come dato in entrata per l'analisi di stabilità secondo il metodo del pendio indefinito. L'utilizzo dell'equazione del Fattore di Sicurezza permette di mettere in relazione la pioggia di progetto con l'innesco delle frane superficiali, tramite il valore h, assumendo dei valori di coesione e angolo di attrito molto bassi.

L'approccio proposto ha lo scopo di studiare le condizioni di innesco delle frane superficiali in relazione a specifiche piogge la cui frequenza è calcolabile, permettendo in questo modo di elaborare delle carte di pericolosità.

Il modello è stato testato in alcune aree delle Colline del Monferrato e delle Langhe (Piemonte meridionale), territori vitivinicoli economicamente molto importanti in cui nel passato si sono innescate migliaia di frane. Le frane superficiali (profondità generalmente inferiori ai 50 centimetri) possono innescarsi solamente considerando un drastico abbassamento dei valori di coesione e di angolo di attrito. Valori di 20° e 0,5 kN/m^2, per l'angolo di attrito e la coesione rispettivamente, in condizioni di totale saturazione, sembra dare buoni risultati nel confronto tra le applicazioni del modello e la carta delle frani reali. Al momento, si stanno effettuando ulteriori test di calibrazione in Alto Monferrato.

TERMINI CHIAVE: Frane riguardanti la coltre superficiale, Pericolosità, Pianificazione territoriale, Piemonte.

GENERALITIES ON SHALLOW LANDSLIDES

Shallow landslides concern the mobilization of the slope detrital cover. They generally involve limited thickness of soil that is saturated by rainwater infiltration as a consequence of severe meteorological events. Campbell (1975) focused on «slides rapidly evolving in flows», and named this type of slope instability as «soil slip-debris flow».

In Italy, the working group at CNR-IRPI investigated the hazard related to shallow landslides in the Piedmont Region (north-western Italy), where slope instabilities are commonly characterized by high rapidity (Govi & *alii*,

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1985 estimated speeds ranging between 2 and 9 m/s), unpredictability of exact source location, and high spatial density (up to some thousands per square kilometre). Despite the limited thickness of involved materials at sources (up to 200 centimetres, but generally less than 50 centimetres) and initial volumes (some hundreds of cubic metres), shallow landslides are commonly characterized by high kinetic energy and destructive power during final phases of development. These processes often show a complex type of movement: the mass in fact starts its movement by sliding and, after a limited displacement, it may liquefy and evolve into a rapid flow; this latter can develop downslope along open slopes or within pre-existing channels.

In the considered area, most of the observed landslides are usually triggered on slopes ranging between 25 and 35 degrees (Govi & *alii*, 1985), with few cases at lower inclinations identified through remote sensing investigations (aerophotogrammetry). The source areas are generally situated in the upper part of the slopes, near sharp slope variations like edges of anthropic terraces and communication routes. Numerous landslides on regular slope are very common, as well as multiple landslides converging inside valleys.

In a study carried out by Regione Piemonte (1998), the shallow landslides triggered in the Langhe hills (Southern Piedmont) after the catastrophic meteorological event of November 1994 were distinguished into four classes (fig. 1), which could be partly ascribed to the same type: A) incipient translational soil slide (Varnes, 1978); B) translational soil slide (Varnes, 1978); C) earth flow (Varnes, 1978); D) disintegrating soil slip (Kesseli, 1943).

The shallow landslides triggered during the 1994 Langhe event were also studied by Casavecchia & *alii* (1998), Sutera Sardo & *alii* (1998), Brizio & *alii* (2000).

Govi & *alii* (1985) claimed that the triggering factor of these shallow landslides was a high amount of water which was rapidly absorbed by the superficial horizon of soil covering a less permeable soil or bedrock. As a consequence, a saturation process, whose velocity is related to the permeability of the superficial soil and to the rainfall rate, could occur. Such a process was in some cases limited to the most superficial soil horizons, but in other cases involved the whole soil cover. As a result, a temporary shallow groundwater circulation, parallel to the slope, developed.

A second scheme of shallow underground water movement was suggested by Masciocco & *alii* (1989), Beretta & *alii* (1995), and De Luca & *alii* (1996), in which the infiltrated rainwater would move downwards from the ground surface through a saturation front, i.e. a well-defined surface that divides an upper saturated layer from a lower one at initial conditions of humidity (Green & Ampt, 1911). Because of the progressive soil saturation, a drastic decrease of soil suction and cohesion occurred up to a critical value, causing the collapse of the soil. According to this scheme, when the soil infiltration velocity is low, the duration of the rainfall has a dominant role in triggering shallow landslides, while rainfall intensity plays a determining role in more permeable soils (Campbell, 1975).

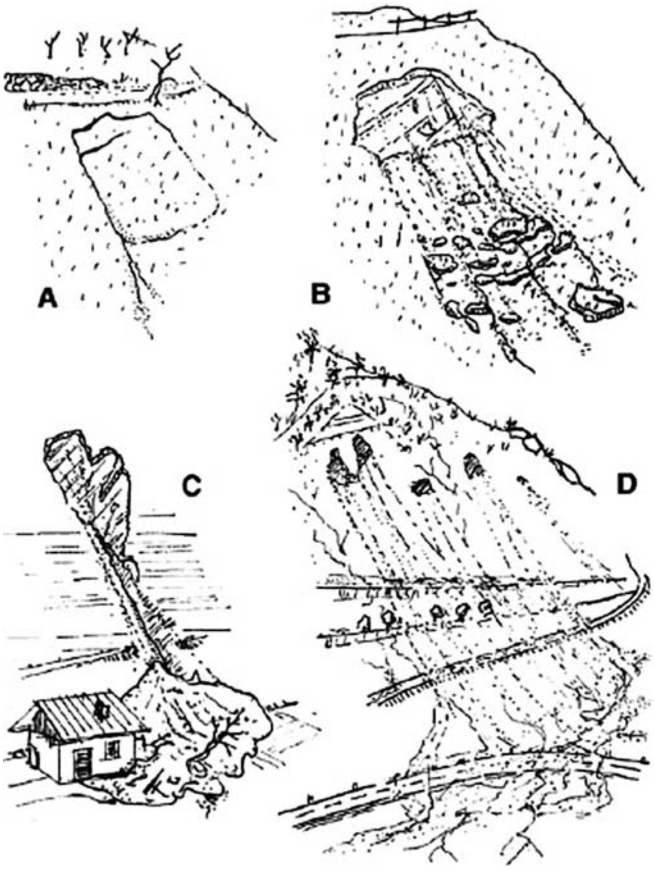

FIG. 1 - Classes of shallow landslides occurred in the Langhe Hills (Southern Piedmont) following the catastrophic meteorological event of November 1994 (Regione Piemonte, 1998). Key: A) incipient translational soil slide, B) translational soil slide, C) earth flow, D) disintegrating soil slip.

EVALUATING THE HAZARD RELATED TO SHALLOW LANDSLIDES

Different methods for the analysis of the hazard related to shallow landslides are available in literature. They can be subdivided in three principal groups: 1) multi-parametric methods; 2) statistical methods; 3) analytical (physically-based) methods.

Multi-parametric methods (e.g. Lee & Pradhan, 2006) are based on the relationships between the spatial distribution of landslides and the parameters affecting the instability of the soil: topography (slope gradient, slope aspect and curvature), lithology, soil type, land use, vegetation (expressed by a *Normalized Difference Vegetation Index*, that depends on the energy reflected in the infrared and red portions of the electromagnetic spectrum) and pluviometry (tab. 1).

Multi-parametric methods are based on the assumption that i) shallow landslides occur due to concurrence of different parameters, and that ii) future landslides will occur in the same conditions as in the past. Accordingly, susceptibility maps can be obtained by superimposing different base maps.

TABLE 1 - Rating of parameters utilised for the analysis of shallow landslides (after Lee & Pradhan, 2006)

Parameter	Class	Parameter	Class	Parameter	Class
Slope aspect	Flat	Land use	Rubber	Soil	Rengam-bukit temiang association
	North		Clear land		
	Northeast		Grass		
	East		Wood		Selangor-kangkong association
	Southeast		Coconut		
	South		Cultivated land		
	Southwest		Wet paddy		Local alluvium-colluvium association
	West		Horticulture		
	Northwest		Mangrove		
Slope (degrees)	0 - 15		Primary forest		Serong series
	16 - 25		Rock		Seep land
	26 - 35		Secondary forest		Kuala kedah - permatang association
	> 35		Tin mine		
Distance from drainage (m)	0 - 50	Precipitation (mm)	2613 - 2651		
	51 - 100		2652 - 2676		Urban land
	101 - 150		2677 - 2695	Normalized Difference Vegetation Index (NDVI)	–73 - –18
	151 - 200		2696 - 2707		–17 - –1
	201 - 250		2708 - 2718		0 - 21
	251 - 300		2719 - 2730		22 - 32
	> 301		2731 - 2742		33 - 37
Distance from lineament (m)	0 - 200		2743 - 2753		38 - 40
	201 - 500		2754 - 2763		41 - 43
	501 - 1000		2764 - 2772		44 - 45
	1001 - 2000	Slope curvatures	Concave	Geology	Micro granite
	2001 - 4000		Flat		Alluvium
	> 4001		Convex		Granite

Some authors addressed the same problem by adopting statistical methodologies, following Campbell (1975) who introduced the concept of «pluviometric threshold». Statistical methods focus on the characteristics of the rainfalls able to trigger the shallow landslides.

Among the models that take into account the characteristics of a specific rainfall event, the most used are those comparing duration and rate of the rains with the resulting landslides. A typical example is the work by Giannechini (2005) in which threshold values for rainfall events causing soil slips were graphically represented by curves (duration vs. rate of rainfall) which separate events that triggered several soil slips, from events which triggered a few soil slips, and events that did not cause significant effects.

Another type of statistical method, frequently used, takes into account the pluviometric conditions before the time of landslide occurrence. Some authors considered only few days before the event (Heyerdahl & *alii*, 2003); others took into account some weeks (Del Maschio & *alii*, 2005) up to 3-4 months (Cardinali & *alii*, 2006), depending on the territory features (lithology, morphology, vegetation, climate) and heterogeneity or lack of data in the pluviometric series.

Among the most complex models, MONSTER (Benedetti & *alii*, 2006) is a deterministic-statistic model composed by a hydrologic section, performed through the Curve Number that permit the rainfall partition between runoff and infiltration, and a statistic one that does not consider physical soil properties, but only the rainfall that triggered the shallow landslides.

Analytical (physically-based) methods also considers the physical features of the soil which affect infiltration of water. Typical examples are HILLFLOW, proposed by Bronstert (1999), and CATFLOW, proposed by Zehe & *alii* (2001), in which several parameters, like precipitations, surface runoff, subsurface runoff, micro- and macroporosity, the root system, soil evaporation and vegetal transpiration, are analyzed. Due to the high number of variables involved, these models are suitable for stability analysis on large scale, but are not easy to implement.

Physically-based models that consider a more limited number of factors were also introduced, by mainly combining hydrological and slope stability models. Among these, an analysis of the transient pressure distribution in response to infiltration was proposed by Baum & *alii* (2002), Montgomery & Dietrich (1994) and Guimares & *alii* (2003), which considered soil saturation and the temporary rising of pore water pressure as the possible cause of shallow landslides. Other authors (Green & Ampt, 1911; Main & Larson, 1971; Pradel & Raad, 1993) assumed the infiltration as a saturation of the first decimetres of soil from the ground surface, considering the formation of a water table at such small depths unlikely.

Regarding the stability model, the majority of authors adopted the indefinite slope method, which is considered the most appropriate for simulating shallow landslides because of the small thickness of the soil involved in relation to the slope length. Montgomery & Dietrich (1994) proposed a physically-based model (SHALSTAB) that assumes stationary hydrological conditions, the presence of a water table, filtration parallel to the slope, total saturation and impermeable bedrock. The model output is a critical value of infiltrated rainfall from which the critical rainfall that causes the landslides can be evaluated. The main limit of this model, besides the stationary condition, is the assumption of no cohesion that does not allow for any comparison with the rainfall frequencies (note that, in such a case, the term *h* disappears in the Safety Factor equation):

$$SF = \frac{f \cdot \gamma_t \cdot h \cdot cosa \cdot cosa + c}{\gamma_t \cdot h \cdot cosa \cdot sena}$$

As explained later, in a physically based model, the saturated soil thickness *h* is the only parameter that permits a direct relation between the rainfall (and its frequency) and the triggering of shallow landslides (and so, indirectly, its frequency).

Another model that considers variations of the pore water pressure is TRIGRS (Baum & *alii*, 2002), based on a hydrologic-mechanical model that, unlike SHALSTAB, enables the simulation of a transitory infiltration process by means of Richard's equation linearization. The model results are largely affected by the initial conditions.

A slightly different approach was proposed by Simoni & *alii* (2006). Their model, GEOTop-SF, combines two consequent models: a hydrological section (GEOtop), dedicated to distributed hydrology, allows for 3-D analysis of soil water content; a stability section, dealing with slope stability, based on the indefinite slope approach. The infiltration water causes an increase of the pore soil pressure and determines a reduction of effective strength and, thus, of soil shearing resistance. Like for the above-mentioned models, GEOtop-SF assumes soil saturation conditions.

A last method analyzed in this brief review combines two products by Geo-Slope Ltd. (1998 a, b) which are related to infiltration (SEEP/W) and to slope stability (SLOPE/W). These models were applied by different authors (e.g. Dapporto & *alii*, 2005; Tofani & *alii*, 2006) for the assessment of susceptibility related to shallow landslides. SEEP/W is a numerical finite elements model based on the equations of motion and mass conservation for the analyses of both saturated and unsaturated groundwater flow. This model can solve problems in static or dynamic conditions. Results can be used as input data for SLOPE/W simulations in order to assess slope stability. SLOPE/W allows for the selection of several limit equilibrium methods (Bishop, 1955; Morgestern & Price, 1965), differing from the indefinite slope concept adopted by other authors. In their study on shallow failures triggered in November 2002 in Valtellina (Northern Italy), Dapporto & *alii* (2005) found that the slope length mostly affected the Safety Factor. Moreover, the most sensitive resistance parameter affecting the Safety Factor was cohesion. When simulating shallow landslides, the use of natural cohesion values in the stability evaluation did not allow for the triggering of landslides. Some authors solved such problem by suppressing the cohesion (e.g. SHALSTAB, by Montgomery & Dietrich, 1994), while others assumed a strong reduction of the natural value (e.g. it is 0,3-0,7 kPa in Van Asch & Sukmantalya Kesumajaya, 1993; 0,5 kPa in Iverson, 2000; 1 kPa in Casadei & *alii*, 2003; 1,5 kPa in Guimares & *alii*, 2003).

THE EVALUATION OF HAZARD RELATED TO SHALLOW LANDSLIDE

A simplified approach for the assessment of hazard related to shallow landslides is proposed in the following sections, in order to provide a practical tool for land planning. In the approach, the downward movement of a humidification front is assumed, according to the scheme proposed by Green & Ampt (1911), which causes the saturation of the superficial part of the soil, whose depth is directly related to the rainfall. Soil saturation causes a drastic decrease in shearing resistance forces and, at certain conditions of saturated depth and slope inclination, the triggering of the landslide.

Also this simplified modelling approach consists of a hydrological (infiltration) section and of a slope stability section, but the relationship with the rainfall rate enables the evaluation of the landslide frequency, making it possible the assessment of shallow landslides hazard.

Infiltration section

Infiltration is the process of water penetrating from the ground surface into the soil. Many factors affect the infiltration rate, among which the condition of the soil surface and its vegetation, and the properties of the soil (such as porosity, permeability and hydraulic conductivity). The infiltration rate indicates the amount of water entering the soil in a time unit. If, during a rainfall, water ponds at surface, then the rainfall intensity is greater than the infiltration capacity of the soil. The elapsed time between the beginning of the rainfall and the water ponding at surface is called «ponding time». At the end of this period, the water in excess begins to flow along the surface, allowing for superficial erosion phenomena.

In this paper, aiming at evaluating the thickness of the saturated soil, which is necessary for the stability modelling section, a method developed by Chow & *alii* (1988) on the basis of Green-Ampt infiltration equation was adopted.

The Green-Ampt equation assumes that infiltration occurs from a water covered surface, i.e. in a «ponding» state, and that terrain and its initial water content are homogeneous. It assumes that water infiltrates forming a wetting front parallel to the ground surface that divides a lower area with moisture content Θ_1 (initial conditions) from an upper saturated area with moisture content $n\Theta_2$ (fig. 2).

Starting from this model, Chow *et alii* (1988) developed two equations for calculating the infiltration, both for lower rainfall intensity than infiltration capacity of soil (eq. 1), and for ponding conditions (eq. 2):

$$F'_{t+\Delta t} = F_t + i_t \cdot \Delta t \qquad \text{(eq. 1)}$$

$$F_{t+\Delta t} - F_t - \psi \cdot \Delta\Theta \cdot \ln\left[\frac{F_{t+\Delta t} + \psi \cdot \Delta\Theta}{F_t + \psi \cdot \Delta\Theta}\right] = K \cdot \Delta t \qquad \text{(eq. 2)}$$

where:

Δt = time interval in which the rainfall event is subdivided;
i_t = rainfall rate (amount of rainfall in the interval time Δt);
F_t = cumulative infiltration at time t;
$F_{t+\Delta t}$ = cumulative infiltration at time $t+\Delta t$ (when rainfall intensity is lower than potential infiltration rate of the soil);

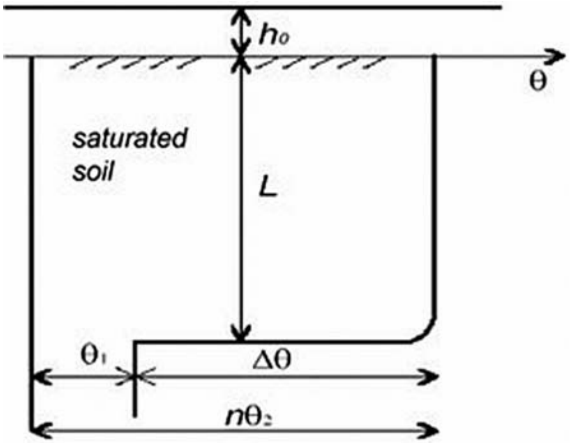

FIG. 2 - Green & Ampt infiltration model (1911).

$F_{t+\Delta t}$ = cumulative infiltration at time $t+\Delta t$ (in ponding conditions);
Ψ = wetting front soil suction head;
$\Delta\Theta$ = difference between the initial and final moisture contents of the soil;
K = hydraulic conductivity of the soil.

For an estimate of the Green-Ampt parameters (K, Ψ and $\Delta\Theta$), the work of Rawls & *alii* (1983), analysing approximately 5000 soil horizons across the United States, can be used.

Depth values of the wetting front are thus calculated using the following equation:

$$H_f = F_t / \Delta\theta \qquad \text{(eq. 3)}$$

Slope stability section

As regards slope stability, the modelling approach is based on the following assumptions: i) indefinite slope; ii) failure surface plane and parallel to the slope; iii) slip surface coincident with the wetting front. The stability conditions of a slope depend upon three main factors: i) slope inclination; ii) soil cohesion; iii) friction angle.

In loose soils, cohesion is equal to zero, so the slope is stable when its inclination is equal or lower than the natural friction angle ϕ. Such angle varies depending upon the type of material, and ranges between 35° and 45° in dry conditions. When the material is wet, the interstitial pressures reduces friction among grains (Benini, 1990).

In cohesive soils, together with friction, cohesion opposes to sliding. Cohesion can have very different values depending on the soil type: it is almost zero in loose soil (gravel, sand, etc.), but it is very high in cohesive rocks; intermediate values characterize semi-cohesive rocks (conglomerate, sandstones, tuffs, altered or split rocks, etc.), while in pseudo-cohesive rocks (silt and clay) it's value depends on the water content (from 0,12 kg/cm^2 for wet clay up to 2 kg/cm^2 for dry clay).

For the stability analysis of an indefinite slope, the geometric parameters and the gravity-related components are considered.

The limit equilibrium equation is:

$$\gamma_t \cdot h \cdot \cos\alpha \cdot \mathrm{sen}\alpha = f \cdot \gamma_t \cdot h \cdot \cos\alpha \cdot \cos\alpha + c \qquad \text{(eq. 4)}$$

where f is the friction coefficient of soil (i.e. tangent of friction angle ϕ), h is the saturated soil thickness, γ_t is the unit weight of terrain, α is the slope angle, and c is the cohesion.

The second member of the equation shows the shearing resistance forces, while the first represents acting forces. Skempton & De Lory (1957) named their ratio as Safety Factor SF:

$$SF = \frac{f \cdot \gamma_t \cdot h \cdot cosa \cdot cosa + c}{\gamma_t \cdot h \cdot cosa \cdot sena} \qquad \text{(eq. 5)}$$

If acting forces are greater than shearing resistance forces, the safety factor is smaller than 1 and the mass becomes unstable.

Shallow landslides (whose depth is generally less than 2 meters, and in Langhe Hills it is about 50 centimeters) can be triggered only considering a drastic reduction of both friction angle (ϕ) and cohesion (c).

Application of the modelling approach

The proposed approach was used for the analysis of susceptibility to shallow landslides on the valuable vineyard *terroir* of Barbera d'Asti D.O.C.G. wine (Albanese & *alii*, 2006) and of Barolo D.O.C.G. wine (Albanese & *alii*, 2008). These territories, respectively located in the Monferrato and Langhe Hills (Piedmont - North-western Italy), were affected by thousand shallow landslides during the catastrophic geo-hydrogeological events of 1993 and 1994 (fig. 3).

The hydraulic parameters (Ψ and K) were obtained through the comparison between the analysis of terrain samples (tab. 2) and the tables proposed by Rawls & *alii* (1983).

The experimental values of soil cohesion c (5-13,7 kPa) and friction angle ϕ (21-31°) do not allow for the triggering of shallow landslides, because of the small thickness of

FIG. 3 - Shallow landslides occurred in Langhe Hills during the geo-hydrological event of November 1994.

TABLE 2 - Classification (USDA, 1998) of soils sampled in the *terroir* of Barolo D.O.C.G. wine

Samples	USDA Classification
ADA 1	Silt clay loam
ADA 2	Loam
ADA 3	Loam
FDL 1	Silt loam
FDL 2	Silt clay loam
FDL 3	Silt clay loam
SAF 1	Silty clay
SAF 2	Loam
SAF 3	Silt clay loam
SAF 4	Silt clay loam

soil generally involved (less than one metre). The values of the *c* and *ϕ* strength parameters were therefore attained through several successive calibrations of the model, with different humidity conditions (tables 3 and 4; figures 4 and 5), by considering data available in literature (Van Asch & Sukmantalya Kesumajaya, 1993). In the tables, only the calibration of cohesion value is showed because the variation of the Safety Factor depends above all on *c* value and less on *ϕ* value.

Calibration led to select friction angle and cohesion values of 20° and 0,5 kPa, as these cause the Stability Factor to fall below the unit for a triggering depth consistent with the observed thickness of shallow landslides (50-100 cm). In fact, the depth achieved by the wetting front, with these cohesion and friction angle values, amount to 95 cm. The parametric values needed for the simulation are listed in table 5.

TABLE 3 - Calibration of model with the use of different value of cohesion and a single value of friction angle (ϕ = 20°), with a $\Delta\theta$ = 0,05 (in bold font the first Safety Factor under the unit)

$\Delta\theta$=0,05	Wetting front depth	Safety Factor					
Time (hours)	**L (cm)**	**c=0,5kPa ϕ=20°**	**c=5kPa ϕ=20°**	**c=2kPa ϕ=20°**	**c=1kPa ϕ=20°**	**c=0,8kPa ϕ=20°**	**c=0,2kPa ϕ=20°**
0	0,00						
1	10,00	1,70	8,90	4,10	2,50	2,18	1,22
2	16,00	1,40	5,90	2,90	1,90	1,70	1,10
3	22,00	1,26	4,54	2,36	1,63	1,48	1,05
4	32,00	1,15	3,40	1,90	1,40	1,30	1,00
5	44,00	1,08	2,72	1,63	1,26	1,19	**0,97**
6	61,15	1,03	2,21	1,42	1,16	1,11	0,95
7	77,30	1,00	1,94	1,31	1,11	1,07	0,94
8	95,68	**0,98**	1,74	1,24	1,07	1,03	0,93
9	109,10	0,97	1,63	1,19	1,05	1,02	0,93
10	122,48	0,97	1,55	1,16	1,03	1,01	0,93
11	135,81	0,96	1,49	1,14	1,02	1,00	0,92
12	149,12	0,95	1,44	1,12	1,01	**0,99**	0,92
13	162,40	0,95	1,39	1,10	1,00	0,98	0,92
14	175,65	0,95	1,36	1,08	**0,99**	0,97	0,92
15	188,89	0,94	1,32	1,07	0,99	0,97	0,92
16	202,11	0,94	1,30	1,06	0,98	0,96	0,92
17	215,32	0,94	1,27	1,05	0,98	0,96	0,92
18	228,52	0,94	1,25	1,04	0,97	0,96	0,91
19	241,70	0,93	1,23	1,03	0,97	0,95	0,91
20	254,88	0,93	1,21	1,03	0,96	0,95	0,91
21	268,04	0,93	1,20	1,02	0,96	0,95	0,91
22	281,20	0,93	1,19	1,01	0,96	0,95	0,91
23	294,35	0,93	1,17	1,01	0,96	0,94	0,91
24	307,50	0,93	1,16	1,00	0,95	0,94	0,91

TABLE 4 - Calibration of model with the use of different value of cohesion and a single value of friction angle (ϕ = 20°), with a $\Delta\theta$ = 0,3 (in bold font the first Safety Factor value under the unit)

$\Delta\theta$=0,3	Wetting front depth	Safety Factor					
Time (hours)	**L (cm)**	**c=0,5kPa ϕ=20°**	**c=5kPa ϕ=20°**	**c=2kPa ϕ=20°**	**c=1kPa ϕ=20°**	**c=0,8kPa ϕ=20°**	**c=0,2kPa ϕ=20°**
0	0,00						
1	1,67	5,70	48,91	20,10	10,50	8,58	2,82
2	2,67	3,90	30,90	12,90	6,90	5,70	2,10
3	3,67	3,08	22,72	9,63	5,26	4,39	1,77
4	5,33	2,40	15,90	6,90	3,90	3,30	1,50
5	7,33	1,99	11,81	5,26	3,08	2,65	1,34
6	10,19	1,69	8,75	4,04	2,47	2,16	1,21
7	12,88	1,52	7,11	3,39	2,14	1,89	1,15
8	15,95	1,40	5,92	2,91	1,90	1,70	1,10
9	18,18	1,34	5,30	2,66	1,78	1,60	1,08
10	20,41	1,29	4,82	2,47	1,68	1,53	1,06
11	22,64	1,25	4,44	2,31	1,61	1,47	1,04
12	24,85	1,22	4,12	2,19	1,54	1,42	1,03
13	27,07	1,20	3,86	2,08	1,49	1,37	1,02
14	29,28	1,17	3,63	1,99	1,45	1,34	1,01
15	31,48	1,16	3,44	1,92	1,41	1,31	1,00
16	33,69	1,14	3,28	1,85	1,38	1,28	1,00
17	35,89	1,12	3,13	1,79	1,35	1,26	**0,99**
18	38,09	1,11	3,00	1,74	1,32	1,24	0,98
19	40,28	1,10	2,89	1,70	1,30	1,22	0,98
20	42,48	1,09	2,78	1,65	1,28	1,20	0,98
21	44,67	1,08	2,69	1,62	1,26	1,19	0,97
22	46,87	1,07	2,61	1,58	1,24	1,17	0,97
23	49,06	1,06	2,53	1,55	1,23	1,16	0,97
24	51,25	1,06	2,46	1,53	1,21	1,15	0,96

In conditions of total saturation, values of 20° and 0.5 kN/m^2 for friction angle and cohesion, respectively, gave good results in the comparison between the model simulations (fig. 6) and the actual landslide maps (fig. 7), these latter obtained through interpretation of aerial photos. In figure 6, the red areas represent the pixels in which the simulated safety factor is lower than the unit.

The comparison between the maps of susceptibility to shallow landslides (fig. 5 b) and of actual landslides (fig. 6) in the *terroir* of Barolo D.O.C.G. wine pointed out an

TABLE 5 - Parametric values needed for the simulation

Parameter	Value
$\Delta\theta$ - difference between the initial and final moisture contents of the soil	0,05 - 0,3
Ψ - cwetting front soil suction head (cm)	8,89 - 16,68
K - saturated hydraulic conductivity (cm/h)	0,34 - 0,65
γ_t - wet bulk density (kN/m^3)	17 - 20
c - cohesion value (kPa)	0,5
ϕ - friction angle value (degrees)	20

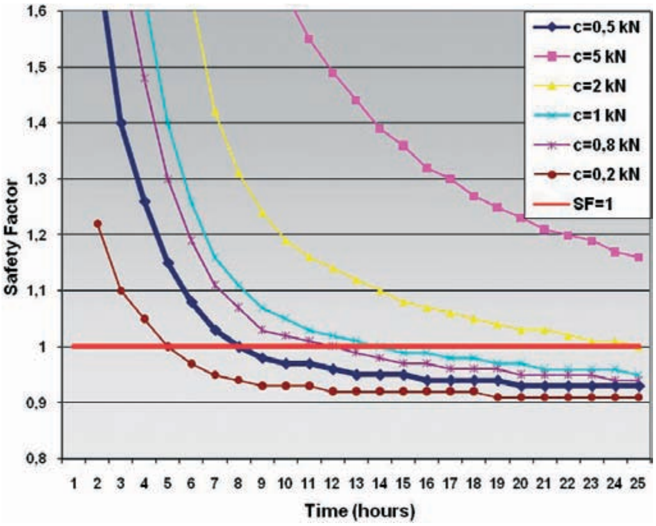

FIG. 4 - Calibration of model with the use of different value of cohesion and a single value of friction angle (ϕ= 20°), with a $\Delta\theta$=0,05 (the blue lines indicates the selected value used in the simulation).

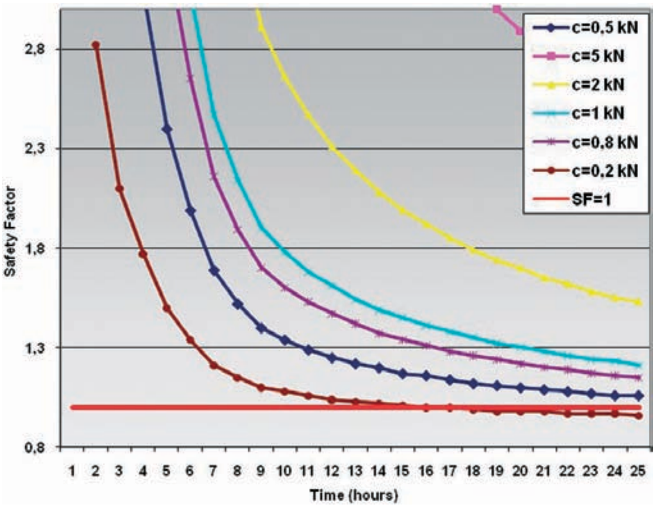

FIG. 5 - Calibration of model with the use of different value of cohesion and a single value of friction angle (ϕ= 20°), with a $\Delta\theta$=0,3.

overlapping of 40% (i.e. the percent of actual landslides which fall in the areas classified as susceptible to shallow landslides); it is a good result, when considering the low precision of the employed DEM 50, with side of square cells of 50 m (the only one available at the moment), which does not enables identification of sharp slope variations.

In the *terroir* of Barbera D.O.C.G. wine, a cumulated rain value of 220 mm in 24 hours (as recorded at the Serole station on September 1993, on occasion of a triggering event in the area) was used as input rainfall data. Instead, in the *terroir* of Barolo D.O.C.G. wine, an observed rainfall hyetograph (fig. 8), related to the flood event of 5-6 November 1994 (fig. 9), was available for the simulation.

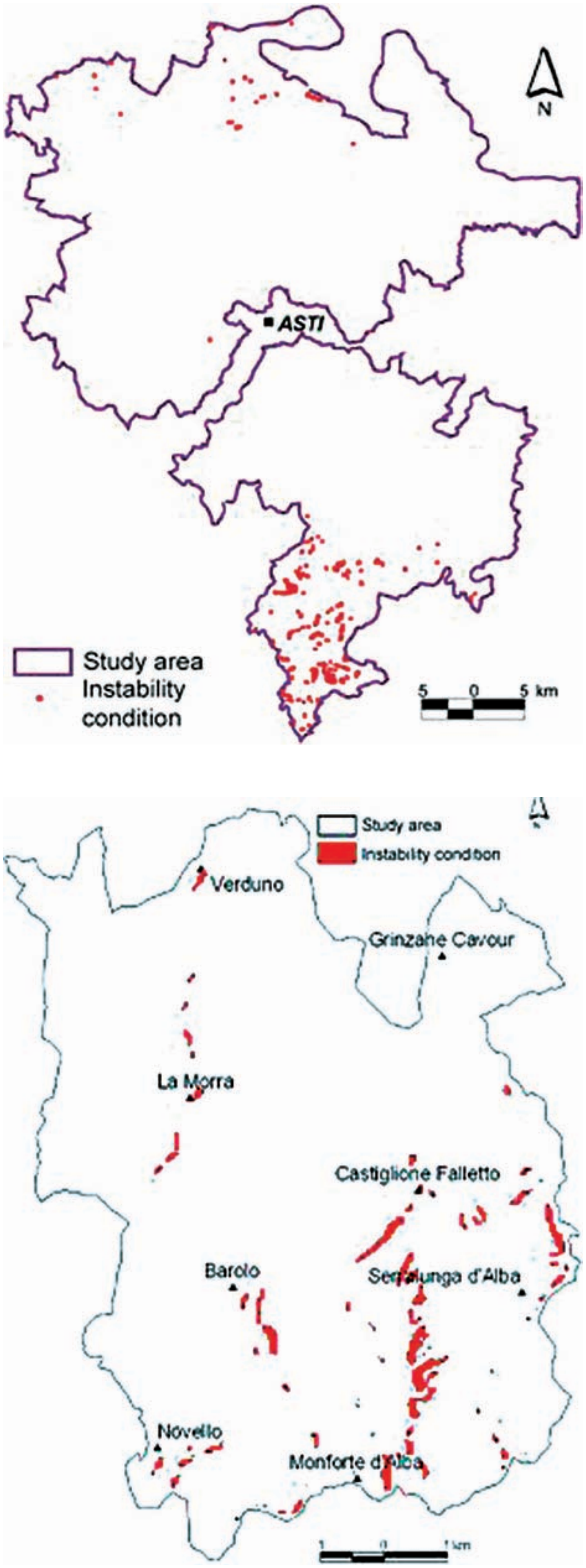

FIG. 6 - Maps of the territories susceptible to shallow landslides as a consequence of a rainfall similar in rate and duration to those of November 1994 event: (up) *terroir* of Barbera d'Asti D.O.C.G. wine; (down) *terroir* of Barolo D.O.C.G. wine.

FIG. 7 - Map of shallow landslides triggered in November 1994 in the *terroir* of Barolo D.O.C.G. wine.

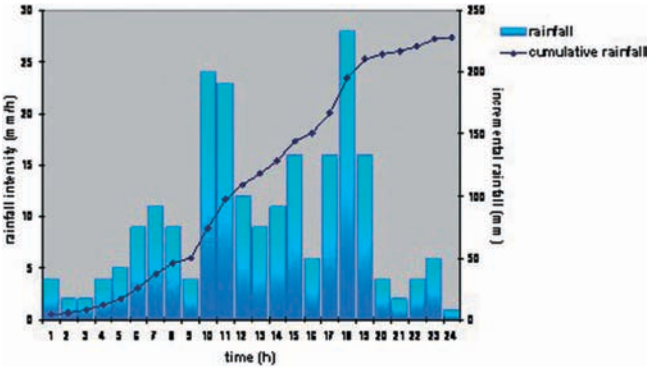

FIG. 8 - Rainfall hyetograph used for simulation in the *terroir* of Barolo D.O.C.G. wine (Treiso station, 5-6 November 1994).

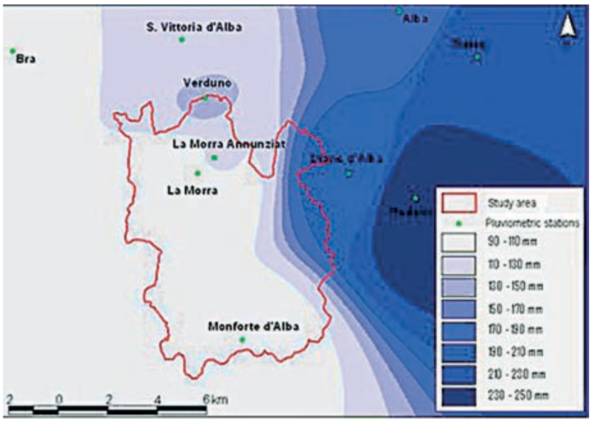

FIG. 9 - Maximum 24 hours rainfall distribution in the *terroir* of Barolo D.O.C.G. wine during the geo-hydrogeological event of 5-6 November 1994.

For both study areas, hourly precipitation data of neighbouring meteorological stations (tables 6 and 7) were processed according to Gumbel's probabilistic method.

From the analysis of the resulting pluviometric curves (fig. 10), the return time of the rainfall used in the simulation was evaluated for each station, making it possible to draw up related frequency maps (figures 11 and 12).

CONCLUSIONS

The advantage of the simplified modelling approach proposed in this paper lies in the need for only few input information and, at the same time, the possibility of calculating the frequency of landslide occurrence.

The applications of the approach for testing the maps of susceptibility to shallow landslides provided encouraging results. The availability of a most accurate DEM will ensure best performances.

TABLE 6 - Maximum hourly precipitation values recorded in the *terroir* of Barbera D.O.C.G. wine

Station	**1h**	**3h**	**6h**	**12h**	**24h**
Serole	58.4	96.0	161.4	185.6	220.4
Casale M.	50.4	69.0	76.0	77.4	84.4
Acqui T.	58.0	64.4	72.2	78.6	111.6
Montaldo S.	44.6	58.8	71.6	84.4	123.4
Montechiaro	44.0	58.8	61.4	86.6	98.2
Nizza M.	46.0	47.0	47.0	60.2	76.4
Asti	25.2	35.8	61.0	87.4	94.2

TABLE 7 - Maximum hourly precipitation values recorded in the *terroir* of Barolo D.O.C.G. wine

Station	**1h**	**3h**	**6h**	**12h**	**24h**
Alba	37.8	80.0	150.0	165.0	181.4
Bra	55.8	63.4	108.0	129.0	139.0
Castiglione F.	32.8	51.0	52.2	61.8	102.8
Castino	33.8	51.0	75.0	113	165.0
La Morra	35.0	60.4	62.8	67.3	112.6
Narzole	36.0	41.0	46.8	67.0	99.0
Verduno	21.6	28.0	34.6	42.2	57.4

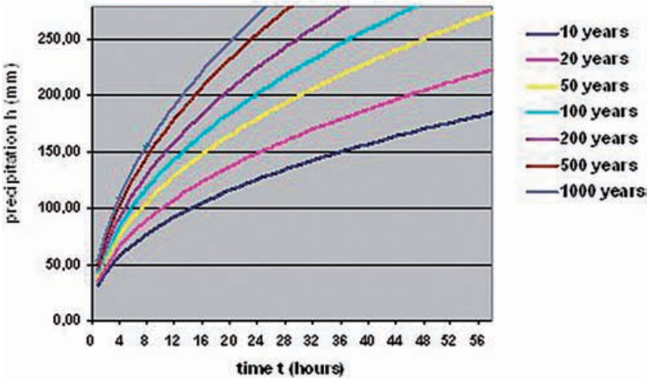

FIG. 10 - Precipitation-duration-return period curves for Alba meteorological station (*terroir* of Barolo D.O.C.G. wine).

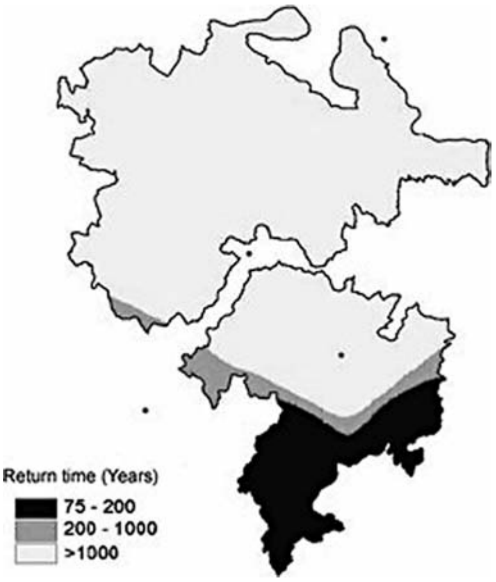

FIG. 11 - Frequency map for the rainfall used in the simulation relative to the *terroir* of Barbera d'Asti D.O.C.G. wine.

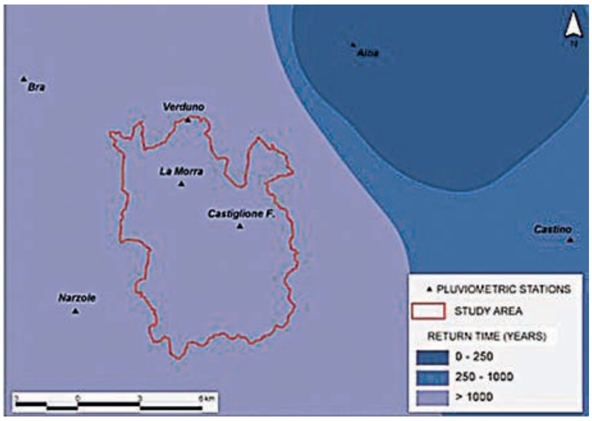

Fig. 12 - Frequency map for the rainfall used in the simulation relative to the *terroir* of Barolo D.O.C.G. wine.

The combined use of maps of susceptibility and rainfall frequency maps allows for the assessment of the hazard related to shallow landslides. The concept of hazard is connected both to the frequency and to the magnitude of that event. While the magnitude of a landslide can be expressed in terms of mass and velocity, the frequency (and the return time) of a landslide can be linked to the frequency (and return time) of the rainfalls able to trigger it.

For instance, in the *terroir* of Barbera D.O.C.G. wine (fig. 13), in relation to the rainfall used in the simulation, the probability of failure in the southern sector of the area is higher (return time = 75-200 years) than in the northern area (return time >1000 years).

In the experiments presented in this paper, susceptibility maps to shallow landslides were drawn up after simulation of single observed rainfalls. Furthermore, an evaluation of the related hazard was derived from the return period maps of the considered rainfall events.

By drawing up different precipitation frequency maps, it will be possible to calculate, for a determined area, the distribution of rainfalls with the same return time (e.g. return period of 50-100-200 years) and duration (e.g. 6-12-24 hours). Using suitable computing systems, different precipitations, similar in frequency and duration, could be elaborated for each land unit (grid cell) according to the proposed simplified methodology, in order to carry out effective maps of hazard related to shallow landslides (e.g. for a return period of 50 years and a rainfall duration of 24 hours).

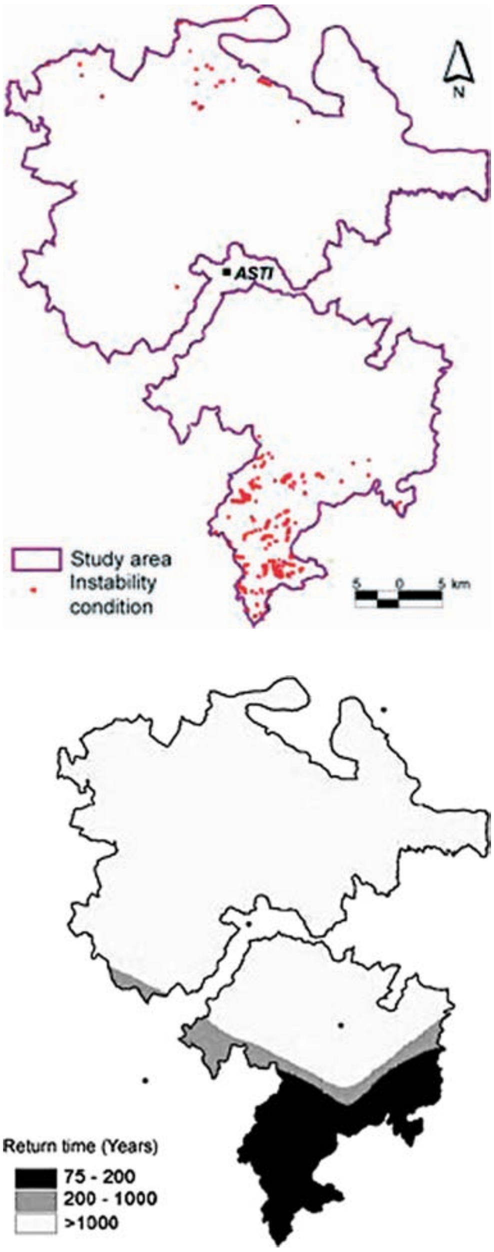

FIG. 13 - The comparison between the map susceptibility (up) and the return time map (down) enables the evaluation of the hazard to shallow landslides in the *terroir* of Barbera D.O.C.G. wine.

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