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An approach to measure soil slip risk

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Abstract

The paper presents a method to assess soil slip risk based on the use of a mechanical simplified model previously introduced by Montrasio [1]. The approach is based on the introduction of the concept of the critical rainy event that induces soil-slip triggering. Two ways to obtain the critical rainy event are presented and discussed.

Furthermore a method to derive the return period of such critical event is proposed. This return period could be directly associated to soil slip risk.

1 Introduction

Soil slips are landslides involving small sections of superficial weakly-bonded soil, usually triggered by brief, heavy rainfall. These phenomena mostly occur on slopes composed of a rocky substrate and a superficial layer of very different permeability characteristics. These phenomena are characterised by a triggering stage and by subsequent development that may occur in different ways [2].

Due to their rapid formation, difficulty in predicting their site and the high distribution density of each phenomenon, soil slips have caused major property damage and casualties. Therefore the economic and social importance of soil slips has made it necessary in recent years to step up research into the problem with the ultimate objective of mapping zones with potential soil slip risk.

Aware of the fact that soil slip risk arises from the product of the danger tied to the main predisposing factors and the vulnerability of a certain territory, this paper primarily deals with assessing some aspects regarding triggering probability of such phenomena.

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2 Recall on the mechanical model

A mechanical model has recently been developed that allows for analysing and describing soil slip triggering mechanism, by calculating the safety factor for a potentially risky slope [1].

The model considers an indefinite slope, since only slight thickness is involved, parallel filtration to the slope and a permeability and strength gradient between the substrate and the superficially weakly-bonded soil. The phenomenon is triggered following loss of the shear strength of the soil, which from an unsaturated state becomes saturated by precipitation.

The safety factor, assessed using the *limit equilibrium method,* results a function of: slope geometry (slope angle β, height H), soil characteristics (specific weight γ_s, porosity n, degree of saturation S), shear strength parameters (effective cohesion c', friction angle ϕ'), thickness of the saturated layer (m) and the water down-flow conditions (k_t).

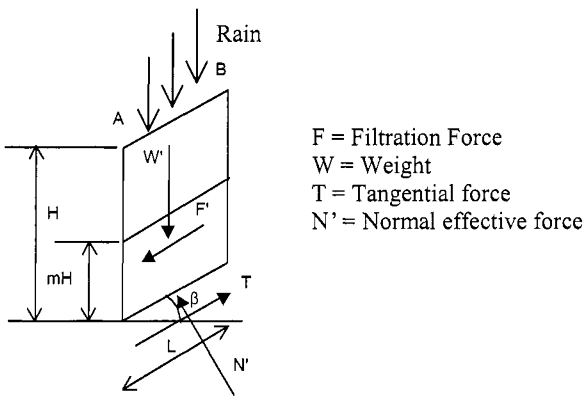

Figure 1: Scheme of the slope and forces acting on the slice.

F_s results:

$$Fs = \frac{\cos^2\beta \cdot tg\phi' \cdot H\gamma_w \cdot [m(n-1)+G_S(1-n)+nS(1-m)] + \left(c' + AS(1-S)^{\lambda} \cdot (1-m)^{\alpha}\right)}{\cos\beta \cdot \mathrm{sen}\beta \cdot H\gamma_w \cdot [m(n-1)+G_S(1-n)+nS(1-m)] + (\gamma_w \mathrm{sen}\beta \cdot \cos\beta \cdot mH)} \quad (1)$$

The shear strength of the unsaturated layer depends on the apparent cohesion c_ψ, that is a function of the degree of saturation S [3], as well as of m through the expression:

$$c_\psi = AS(1-S)^{\lambda}(1-m)^{\alpha} \quad (2)$$

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where A and λ are parameters that have been introduced interpreting the Fredlund et al. [4] experimental results on unsaturated silty soils, and α is a parameter that has been derived from experimental model texts on an indefinite slope.

The model envisions a link between the saturated layer height, mH, and the amount of precipitation (or the height of rain), h, which is regulated, if more than a single rainy episode occurs, by the water down-flow [5], [6]. This allows for directly correlating the safety factor to the amount of rainfall by taking into consideration previous rains.

The following expression of $m(t)$ is obtained:

$$m(t) = \sum_i e^{-k_T \cdot \frac{\operatorname{sen}\beta}{nl\cdot(1-S)}\cdot(t-t_{0i})} \cdot \frac{h(t_{0i})}{nH\,(1-S)} \tag{3}$$

where k_t is the tangential permeability coefficient and t_{oi} the instant at which the pluviometric event $h(t_{oi})$ is referred.

Many numerical analysis showed that F_s depends decisively on S, on k_t and on $h(t)$ while is less influenced by geometry, by other soil characteristics and by the shear strength [7].

3 Definition of the 'risk' concept

Equations (1) and (3) permit to derive the safety factor for a slope, potentially at risk of soil slip, given a datum pluviometric diagram but don't give any information on the probability that F_s becomes 1.

Based on the observation that instability occurs when a certain critical rainy event (h_{cr}) verifies, to assess risk firstly h_{cr} has to be derived for a datum slope.

The major difficulty in doing this, is represented by the fact that the same rainy event cannot be considered a priori a critical event, because of the dependence of its criticise from the previous trend of the pluviometric diagram.

Known the h_{cr} causing F_s=1 the return period of such event can be derived basing on a conspicuous number of pluviometric diagrams for the examined zone. The probability that slope instability occurs, and consequently the risk, can be associated to such return period.

4 Definition of the critical rainy event h$_{cr}$

In the following paragraphs two different approaches to define h_{cr} are proposed and compared. The former, named 'simplified method' is a deterministic method, based on the definition of a 'medium' trend of the pluviometric diagram and on the successive derivation of h_{cr}. The latter is a statistical one based on the definition of a series of 'artificial' pluviometric diagrams, derived employing the Monte-Carlo technique.

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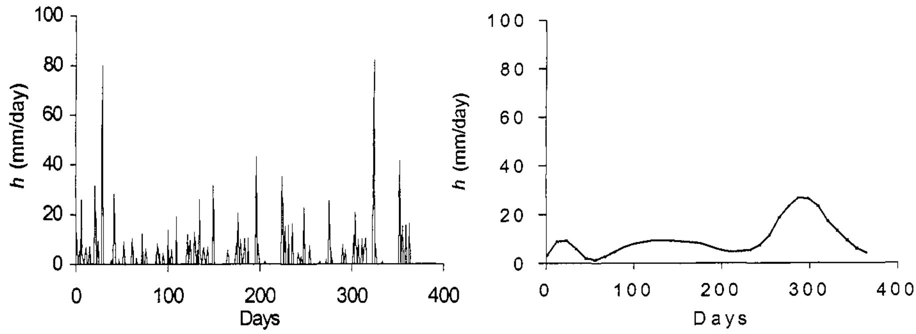
4.1 Simplified method

4.1.1 The concept of "medium" pluviometric diagram

The "medium" pluviometric diagram can be obtained from the analysis of a certain number in the following way: for every day of the year the medium *h* is considered as sum of all the *h* verified in each year at the same day, divided for the number of years considered. The sum excludes the anomalous peak of the pluviometric diagrams. Doing so the amount of the daily water foreseen by the 'medium' pluviometric diagram, so derived, is naturally exceeding the real one, because all the days of the year presumably result rainy.

Figure 2a shows an example of annual pluviometric diagram relative to Acquiterme, sited in Piedmont Region (Italy), where a conspicuous number of soil slips occurred in 1994, during Piedmont flood (Montrasio [1]).

Figure 2b instead shows an example of "medium" pluviometric obtained referring to 1990-1997 period from the same pluviometric station.



(a) (b)

Figure 2: Annual (a) and "Medium"(b) pluviometric diagram derived for Acquiterme (Piedmont- Italy).

It can be observed that the trend is characterised by a maximum *h* in autumn and a minimum in winter. The maximum *h* is about 25mm in a day that is a value well inferior to the one (about 85 mm) that induced soil slips in 1994 (corresponding to the maximum peak of Figure 2a).

After the "medium" trend is identified since the soil's geotechnical characteristics were known, managing equations (1) and (3) it was possible to calculate the safety factor, which, as is plausible, has always been greater than one. This has been done for a slope, site of soil slip in 1994, and well characterised by a geotechnical point of view (Montrasio [1]). .

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4.1.2 Determination of h_{cr}

Now the critical rainy event capable of causing slope instability can be assessed. This can be done superimposing an exceptional rainy event to the "medium" pluviometric diagram in various periods of the year. The assessment can be made using the expression obtained by eqn (1):

$$m = \frac{\cos\beta \cdot H\gamma_w \cdot (G_S - G_S n + nS) \cdot (\cos\beta \cdot tg\phi - F_S \cdot sen\beta) + c' + A \cdot S - A \cdot S^{1+\lambda}}{\cos\beta \cdot H\gamma_w \cdot (n - nS) \cdot (F_S \cdot sen\beta - \cos\beta \cdot tg\phi) + A \cdot S - A \cdot S^{1+\lambda}} \tag{4}$$

Assuming that F_s=1, in order to determine critical rainfall on a given day t', the link expressed by (4) is considered by subtracting the contributions of m from $m(t')$ due to previous rains; the following is obtained:

$$m^* = e^{-kT \cdot \frac{sen\beta}{nl \cdot (1-S)} \cdot (t'-t')} \cdot \frac{h(t')}{nH(1-S)} \tag{5}$$

which represents the value of m due only to rains fallen on the day considered.

One manages to obtain

$$h_{cr}(t') = m^* nH(1-S). \tag{6}$$

where n is the porosity of the soil.

4.2 The Monte-Carlo technique

Another way to obtain the critical rainy event that causes instability consists in generating some 'artificial' pluviometric diagrams, characterised by statistical trends and by absolute peaks of different heights.

A new series of hydrological data randomly extracted from a random variable population distributed according to a pre-set principle can be generated. The extraction of a series of values from a random variable population may always be traced to extraction of a series of values from the population of an evenly distributed variable (with constant probability density in all of the existing field) in the interval (0-1).

In this work the Monte Carlo method has been applied in the following manner: firstly were taken into consideration precipitation data, through which one knew the probability density curve and the cumulative probability; a random number, variable between 0 and 1, with uniform density (equal to 1) and linear cumulative probability, was extracted; than was obtained a value of h (y = f(h)

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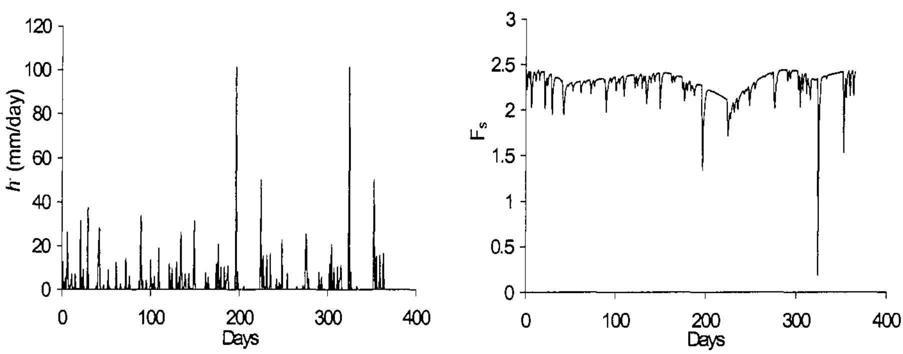
⇒ h = g(y) ⇒ h = g(RND2)) and finally 365 values of h, reproducing an annual precipitation chart and giving the same probability curve, were obtained.

A further analysis of the randomly extracted values has allowed for taking into consideration the fact that on an annual precipitation chart one has on average (from the statistical viewpoint) 25% precipitation data and 75% precipitation-free data.

By assuming a different maximum peak rainfall value (h_{max}) for each calculation process and accepting a maximum deviation of 10mm, in absolute value, between the peak obtained and the required one, different precipitation charts were generated. Only one precipitation chart was generated for each h_{max} set and the relative trend of F_s was calculated by using eqn (1) and eqn (4); by varying $h_{max,}$ the value of h at which the slope started to become unstable was obtained.

For example, assuming h_{max}=104mm, the annual precipitation chart (Figure 3a) and relative trend of Fs (Figure 3b) were generated.



(a) (b)

Figure 3: An example of a precipitation chart generated with the Monte Carlo method, assuming h_{max}=104mm (a) and relative safety factor trend (b).

An analysis of these data reveals that precipitation charts with more peaks give a higher minimum safety factor. This fact emphasises once again the importance previous rains have in determining the value of F_s. If a high rain peak is preceded by precipitation-free days, one may obtain a greater F_s than in the case of a lower h_{max}, but following days with precipitation.

In these analyses one has partly lost the statistical and probabilistic aspect, since only annual precipitation charts were analysed for each h_{max} value and the resulting observations were obtained from only one example of h trend. And since it was determined randomly through extraction of random numbers, it does not encompass infinite h trends that may be delineated over the years.

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5 Return period of a critical event

The return period T_R of the critical rainfall event (that causes instability of the slope) can be simply determined as the ratio between the entire time considered and the number of events of the same type in the same period.

Unfortunately this method isn't satisfactory. In fact using daily precipitation data recorded at the Acquiterme Meteorological Station, for the years 1914-1986, the return period evaluated by this way was, for a critical rainy event h_{cr}=111mm, only 14 years. It means that every 14 years the slope becomes unstable, which cannot be confirmed in reality.

This method was easy to apply unless precipitation data concerning a sufficiently long period of time is available to make a more precise assessment of return periods. Lacking sufficient data, it is necessary to introduce a statistical approach so as to generate a greater amount of data.

5.1 A statistical approach

The approach is explained through a practical example. The analysis is performed for the Acquiterme station, for which a total of 25664 rainfall data were available for the years 1914-1986 and 1990-1997, 6163 (24.01%) of which concerned days with precipitation. Rainfall measured totalled 52554.28 mm, with an average value out of the total data of 2.047mm per day, 8.52 mm concerning only days with precipitation. One may consider the amount of rainfall (h) as a continuous random variable and all available data as the population of the random variable. The probability density curve $p(h)$ was drawn using the 6613 data concerning days with precipitation, and histograms were used to illustrate the number of days on which recorded rainfall in mm was within the following value intervals: (0-1], (1-2], (2-3], (3-4], ...(200-201].

For each rainfall interval, the number N_f of days on which that rainfall verifies was found, and since the total number of days with precipitation N is known (N=6163), the probability of occurrence of a given rainfall event is defined as:

$$p = N_f / (N \cdot \Delta)$$

where Δ is the breadth of the interval of the amounts of rainfall considered. By assigning the probability p to an amount of rainfall (in mm) equal to the mean value of each value interval considered (0.5, 1.5, 2.5, 3.5,...) the probability

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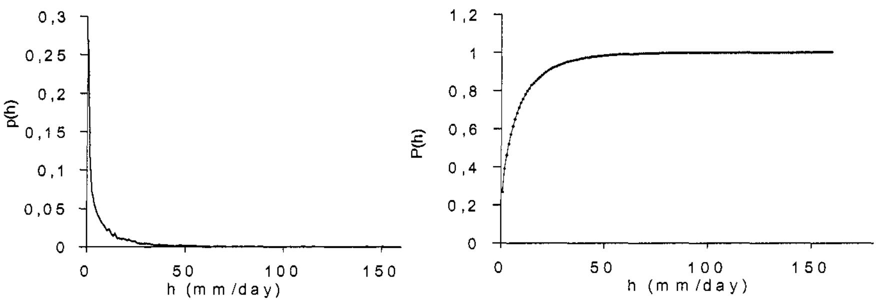
density function was drawn (Figure 4a). Starting from "discreet" data, the function *P(h)* was defined as:

$$P(h) = \int_0^h p(h)dh \qquad (8)$$

which, for each random variable *h*, gives the probability that the same variable does not assume a higher value than *h* (non overcoming probability function, Figure 4b).



(a) (b)

Figure 4: Chart of probability density function (a) and the "non overcoming probability " (b) referring only to days with precipitation.

Analysing the cumulative probability one realises that for *h*=60mm one already has a non-overcoming probability equal to 0.99, i.e. only the 1% probability of overcoming that rainfall value. This makes it obvious that the data available are not indicative for higher values of *h*. Afterwards it would be advisable to refer to real data up to rainfall amounts of 60mm by using a forecast model for higher values.

The next step is to define the return period of a rainfall event, which, from the statistical viewpoint, is given by the expression:

$$T(h) = \frac{1}{1 - P(h)}\,. \qquad (9)$$

being *h* the random variable and *P(h)* the corresponding non-overcoming probability function.

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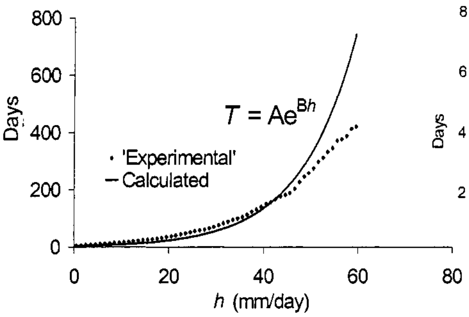
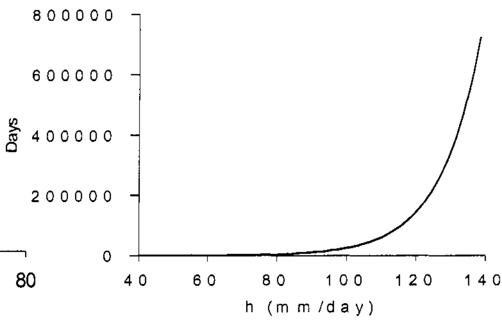
A forecast model able to define return period trends for all h values can be based on an exponential function of equation:

$$T = Ae^{Bh}. \tag{10}$$

Parameters A and B are determined in order to fit both data referring to all days, considering values of h less than 60mm (Figure 5a), and the probability curves obtained from trial data (Figure 4), taking into account that in the latter case A=1, considering only days with precipitation. A and B values that best interpolates the return period trend obtained from trial data in this example are 4.16 and 0.087 respectively (Figure 5).



(a)



(b)

Figure 5: Mathematical curve interpolating return period for rainfall measuring less than 60mm (a) and mathematical curve of return period referring to all of the data (b).

Managing eqns (9) and (10) return periods may be calculated.

Some meaningful values obtained with that method concerning Acquiterme are shown in Table 1 (Mari [8]).

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Table 1: Return periods of significant rains for Acquiterme.

Total rainfall on one day (mm/day)	Return period	Total rainfall on one day (mm/day)	Return period
0.5	5.7 days	80.5	12 years
10.5	17.2 days	90.5	30 years
20.5	37.6 days	100.5	72 years
30.5	76.8 days	110.5	172 years
40.5	151.8 days	120.5	412 years
50.5	276 days	130.5	986 years
60.5	2 years	140.5	2357 years
70.5	5 years	149.5	5163 years

Knowing the h_{cr} value for a given slope the return period of such event can be derived. The return period could be considered reasonably true.

6 Application example

It is considered the Acquiterme zone, where soil-slip occurred in 1994. Since the site is well characterised by a geotechnical point of view (Montrasio [1]) and a conspicuous number of pluviometric diagrams are at disposal, it is possible to derive the return period of a critical rainy event inducing soil-slip.

Since the more realistic h_{cr} seems obtainable from the simplified method instead of the Monte-Carlo technique, the h_{cr} value is derived using the 'medium' pluviometric diagram concept and the superimposition of peak rainy events to it.

The parameters employed to introduce in expression (4) and (5) are shown in Table 2.

Table 2: Parameters regarding soil characteristics.

Gs		γ_d	n	H		k_t		A	
2.7	45°	1.4 g/cm^3	0.45	1m	27°	10^{-6}m/s	0.4	100	3.4

The h_{cr} value results to be about 120mm: it is well below the height of the rainy event causing a conspicuous number of soil slip during the 1994 flood that

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oversaw 200mm. The return period of such event determined by using Table 1 results to be 410 years.

7 Conclusions

The paper has shown a method to measure the 'risk' that soil slips occur through the introduction of the critical rainy event concept and of the return period of such event. The determination of them can be made in some ways (statistical or not) and the methods are presented.

From an analysis of the results obtained by using the methods described above, some merits and limits emerge that lead us to believe that the best method to define the return period is to mix the simplified method of deriving h_{cr} and the statistical method of deriving T_r. The method also uses data consisting of all precipitation recorded at a given meteorological station. Based on these data, the "medium" pluviometric diagram for the zone is identified and consequently rain peaks that trigger instability phenomena are determined.

From these extraordinary events, return periods are calculated by applying the relation (9) concerning the statistical method, but by reverting to real data if h_{max}<60mm, and to the results obtained with introduction of the mathematical function interpolating the real curve when h_{max}>60mm.

In order to map soil slip risk, it's necessary to identify in the environment under observation zones in which some factors predisposing those phenomena may be considered constant.

Basing on this method it can be proposed a way to obtain risk maps employing the approaches presented to define Fs, h_{cr} and Tr [8].

Acknowledgements

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