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Stability analysis of soil-slip

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Abstract

This paper presents a simplified method for the assessment of the safety factor of slopes potentially at risk of soil-slip (superficial plane sliding movements). These are slopes consisting of a bedrock and a thin superficial sheet of relatively weakly-bonded, primarily muddy soil with sand and clay interbedding.
It deals with the hypothesis determining the definition of the safety factor deriving from the limiting equilibrium method, and with the factors contributing to put a slope at risk. The diagrams of the variation of the safety factor in time according to the variation of factors that most influence its course are presented. The analysis results highlight the decisive role played by pluviometric diagram and soil water downflow as the two key factors.
Finally, an analysis has been carried out of the variation of the safety factor of a slope subject to soil-slips during the flood that hit the Piedmont region (Northern Italy) in November 1994 that was recently the object of geotechnical characterisation.

1 Introduction

The term soil-slip generally identifies landslides of a specific nature in pre-Alpine or hilly areas, slopes consisting of a relatively thin debris sheet (1-1.2m maximum) and a bedrock. The interest for such events, little studied so far, resulted especially following the 1994 flood in the Piedmont region when thousands of soil-slips caused considerable structural damage and a high death toll on 5-6 November of that year. Figure 1 illustrates a slope in the Cerretto Langhe area (Piedmont – Northern Italy), the site of a number of landslides of this type and presents a typical example of soil-slip occurred in 1993 in Valtellina (Lombardy- Northern Italy) that caused serious property damage as the rapid slide flow travelled for dozens of meters at a speed of a couple of

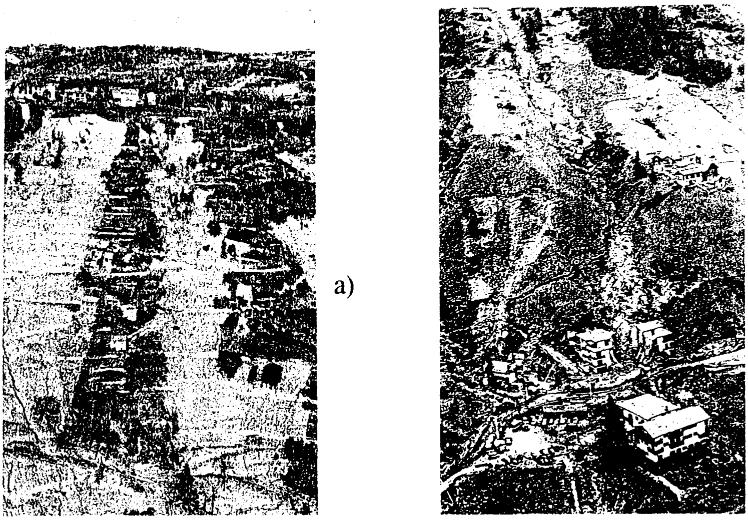

Figure 1: Typical soil-slip occurred in: a) Cerretto Langhe (Piedmont) during the flood in November 1994; b) in Val Tartano (Valtellina - Northern Italy). After Campus et al. [1].

meters per second. There was a considerable spread of such events in the Piedmont region during the flood (Campus et al. [1]).

2 Definition of typical soil-slip characteristics

Campus et al. [1] described the results of a census of soil-slips that occurred during the 1994 flood in Piedmont and in particular of a statistical analysis based on data relating to both the main characteristics of the events and their causes.

In particular the average slope angle β of slopes subject to soil-slip was estimated at around 48°; the average landslide width d at ca. 20m; the average length L at ca. 9.5m and the average thickness H at 0.98m. The superficial sheet mainly consists of silt and a low percentage of clay with sand interbedding. The slip usually does not occur in the contact area between the nappe and bedrock but rather a few cm's above, within the nappe itself.

The major contributing factors to the occurrence of such events were identified in intense and abundant rainfall followed by precipitation of exceptional intensity.

Figure 2 presents a typical pluviometric diagram of the flood area for the year 1994, showing the exceptional nature of precipitation on 5 November which triggered almost simultaneously the vast majority of soil-slips, which followed a period of quite intense rain.

The evolution of the event following the triggering factor can vary: the sliding soil portion can be displaced by a few dozen meters or several dozens thereby

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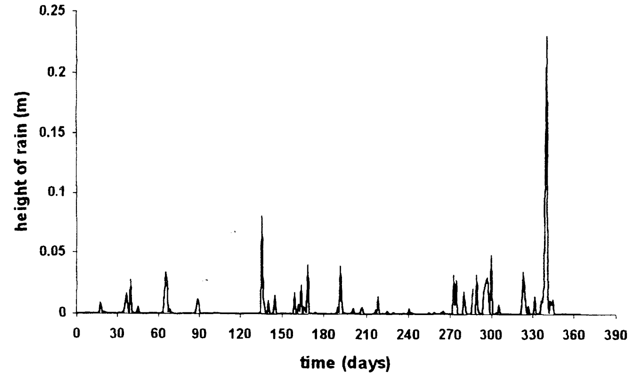

Figure 2: Typical yearly pluviometric diagram (provided by the Pluviometric Station in Treiso) for the areas affected by the 1994 flood.

becoming a channelled flow or an almost fluid mass running down the surface of the slope. In this case, the speed of the flow can reach 9m/s.
The model under analysis is aimed at determining the very onset of such events, depending on the soil mechanical and hydraulic characteristics and the extent of precipitation without focusing on the actual evolution of the landslide. It was devised on the basis of the characteristics of slopes subject to soil-slip to offer a simplified yet accurate description of the factors that determine the risk of soil-slips in a slope, in order to determine, through a statistical approach, the actual landslide hazard for entire areas.
The stability analysis led to the definition of safety factor, based on the outline of an undefined slope, on a number of hypotheses on the events that brought to the landslide and finally on the limiting equilibrium method. The method presented here is intentionally simplified in view of its objective, namely the mapping of at-risk areas.

3 Outline of the problem

The problem was outlined following the evolution that can be described as follows:

1. For the purpose of this study, the slope is considered infinite and initially characterised by a sheet of non-saturated soil of thickness H and a rigid and impermeable bedding. The slope is stable, even in case of slope angles greater than the shear strength coefficient ϕ thanks to the partial saturation which determines an apparent cohesion $c\psi$ depending upon the degree of saturation itself (Fredlund et al. [2], Peterson [3]). For the same reason, stable silt slopes that would normally tolerate a maximum shear strength angle of 30° remain stable even with slope angles of 50-55°.
2. Rainwater rapidly penetrates the nappe reaching the impermeable bedrock, saturating it from the bottom as it mounts again, generating a saturated

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bedding of thickness (*mH*) dependent on the infiltrating water column and on the porous nature and initial saturation of the soil.
Obviously, this hypothesis does not allow a rigorous representation of the flow resulting from rainwater infiltration in the soil, which depends on the initial conditions of soil humidity, the amount of infiltrating water and the soil hydraulic characteristics (Alonso et al [4], Bear [5]). These infiltration models are based on an ideal porous medium, with a degree of permeability varying according to the porous nature of the soil and its degree of saturation, all characteristics that can be brought back to soil volume.
Experimental studies of the superficial nappe of slopes subject to soil-slips indicated that even though the silt present in the soil normally does not justify a high permeability degree, a thick network of small, prevalently vertical channels linked to the soil surface characteristics (Interreg Report [6]) gives rise to a sort of double porosity which accounts for a degree of vertical permeability of soil considerably higher than that to be expected on the basis of soil volume porosity. A series of infiltrometric field tests with the aid of a rain-simulator, used to recreate precipitation of an intensity of 100mm/h and a duration of a few hours in slope areas with different slope angles and humidity characteristics (Mari [7]), has confirmed these hypotheses. That rainwater should instantly reach the bedrock is obviously highly unlikely with precipitation of modest entity whereby rainwater infiltrates, and alters the degree of saturation of superficial strata only, without reaching the impermeable bedrock. This can reasonably occur in the event of intense precipitation which, it must be noted, contributes significantly to destabilise slopes, whereas the pattern of infiltration of modest rainfall in this context is to be considered almost totally irrelevant.

3. When the point of saturation is reached, water starts its downflow parallel to the slope, generating a decrease of *m* in time until the initial conditions are restored, with *m*=0.
   This mechanism can be generalised in the event of repeated precipitation with stratum thickness *mH* which equals to the total sum of all *mH'* of previous events, each quenched starting from its onset.

4 Definition of safety factor

The outline of the slope is based on an indefinite slope and the safety factor, calculated on the basis of the limiting equilibrium method, is identified as a ratio between the stabilising tangential force T_s and the destabilising tangential force T_d on a slice as in Figure 5:

$$F_s = \frac{T_S}{T_D} \qquad (1)$$

where $T_d = W' \sin\beta + F'$ (2)

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where W' is the slice's weight; F' the filtration force developing in the saturated sheet of thickness mH as a consequence of the filtration parallel to the slope; β the slope angle.

The destabilising force results from the integration of the Mohr-Coulomb failure criterion modified to account for partial soil saturation:

$$T_s = N' \tan\phi' + [c'+c_\psi(S)]L \tag{3}$$

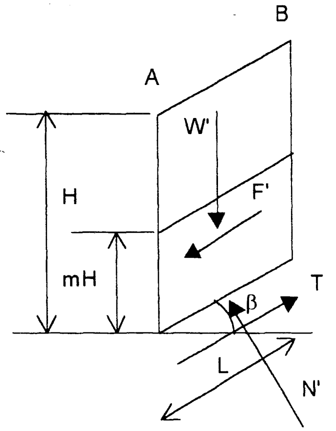

Figure 3: Forces acting on a slice

where φ' is the soil shear strength angle ; c' the effective saturated soil cohesion; L the slice length and N' the normal effective force.

The expression $c_\psi(S)$ represents the effect of partial saturation and can be expressed as follows:

$c_\psi(S)= c_\psi^*(S) f(m)$

Where c_ψ^* represents the effect of partial saturation on soil shear strength and can be directly referred to the degree of saturation by processing the link proposed in Fredlund et al. [2]. With the introduction of *f(m)* the shear strength of the saturated layer is hypothetically assumed to be influenced by the unsaturated one.

The expression of $c_\psi(S)$ is as follows:

$$c_\psi(S)= A\, S\, (1-S)^\lambda (1-m)^\alpha \tag{4}$$

where S is the degree of saturation;

A and λ are parameters that depend on soil characteristics and best illustrate the link between apparent cohesion and the degree of saturation based on Fredlund et al. [2]. In particular, with A=100 and λ=0.4, the curve based on Fredlund et al. [2] for silt is identified with considerable accuracy. α is a parameter allowing for the 'homogenisation' of shear strength characteristics of the stratified soil and can be obtained through experimental testing.

Their value is based on tests performed at the Civil Engineering Dept. of the Parma University on a model unlimited slope made of bedded soil, with a sheet of dry soil of thickness *mH* and a sheet of partially saturated soil of thickness *(1-m)H*. Experimental results, providing the pattern of variation of the slope critical steep angle according to the variation of dry soil thickness *mH* have indicated

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that, based on experimental back-analysis, the value of α is almost equal to 3. The expression of N' is based on the following:

$$N' = W' \cos\beta \quad (5)$$

Where

$$W' = L\cos\beta \, H \, \gamma_w[m(n-1) + G_S(1-n) + nS(1-m)] \quad (6)$$

where n = soil porosity; G_s = specific weight of the solid structure in relation to γ_w; γ_w = specific weight of water.
The expression of F_s based on (1), (2), (3), (4) and (5), is therefore:

$$F_s = \frac{\cos\beta H\gamma_w[m(n-1)+ GS(1-n)+ nS(1-m)] \cos\beta\tan\phi + [c' + AS(1-S)^{\lambda}(1-m)^{\alpha}]}{\cos\beta H\gamma_w[m(n-1)+ GS(1-n)+ nS(1-m)]\sin\beta + \gamma_w \sin\beta \; mH \cos\beta} \quad (7)$$

depending on geometrical factors (β and H), soil and water characteristics (G_s and γ_w), soil conditions (n, S), shear strength (c', ϕ') and three parameters (A, λ and α) based on the soil type.

5 Model of water downflow

In a soil sheet of slope angle β and height H, characterised initially by a degree of saturation S and porosity n, the ratio between the height of the infiltrating water column and the sheet thickness saturating as a consequence of infiltration mH is as follows:

$$m = \frac{h}{nH(1-S)} \quad (8)$$

The water downflow model is expected to follow the evolution outlined in figure 9 for a portion of slope of length L (site of the downflow). In particular, situation A (saturated bedding, thickness mH) evolves into situation B (bedding of thickness mH returning to its initial partially-saturated condition) as a consequence of parallel downflow to the slope.
With a coefficient of permeability parallel to the slope, k_t, the hydraulic conditions in figure 4 led to the following expression of $m(t)$

$$: m(t) = \frac{h_o}{nH(1-S)} e^{-k_T \frac{\sin\beta}{nL(1-S)}(t-t_o)} \quad (9)$$

where h_o = value of at a point in time t=t_o. When considering a series of rainfalls (h_{oi}), each occurring at a specific point in time t_{oi},, $m(t)$ becomes the total sum of all $m_i(t)$ each resulting from its corresponding h_{oi} quenched by the respective quenching factor from the time t_{oi} until the time t when $m(t)$ is assessed. In short:

$$m(t) = \sum_i e^{-k_T \frac{\sin\beta}{nL(1-S)}(t-t_{oi})} \frac{h(t_{oi})}{nH(1-S)} \quad (10)$$

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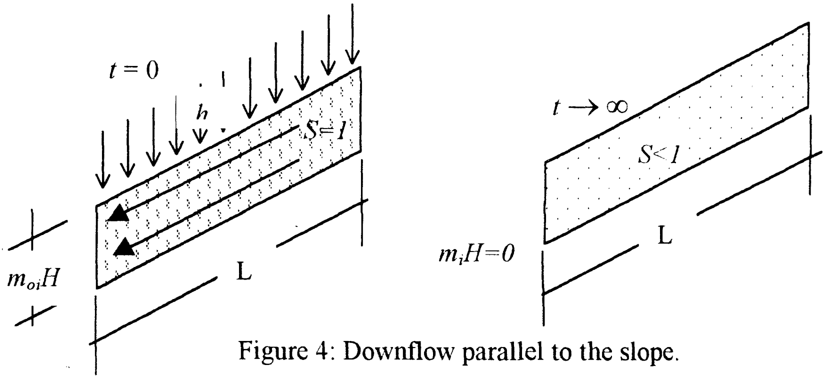

Figure 4: Downflow parallel to the slope.

6 Time variation of safety factor

Introducing expression (10) into (7), the safety factor F_s varying according to time t is obtained on the basis of previously described factors and of another two parameters, namely the coefficient of tangential permeability k_t and length L. Given the considerable practical difficulty in determining the value of the latter, its value was estimated to be equal to 1, determining the value of k_t on the basis of back analysis, in which case it comes to indicate not the coefficient of local permeability but rather a total drainage capacity.
Based on geotechnical analysis of slopes subject to soil-slip in November 1994 and on the pluviometric diagram in figure 2 using average values for all F_s relevant factors as derived from the characterisation of the soil slips, it was possible to draw up F_s-t curves. Figure 5 and 6 present F_s variations in time determined by the two most important factors, namely degree of saturation and drainage capacity k_t; less significant variation is recorded with change in value of β, ϕ, n and H. The values set for the other parameters are: $\alpha = 3$, A=100, λ = 0.4; G_s= 2.7, γ_w = 10 kN/m^3, β=45° , ϕ=27° , n=0.45 , e H=1m.
As the degree of saturation changes, (in this case, $k_t = 10^{-6}$ m/s), the slope is stable at all times with the exception of the time of maximum rainfall, when F_s falls below 1 at all degrees of saturation (figure 5).
When S = 0.8, F_s falls below 1 at different points in time, which may depend on the fact that S = 0.8 is not a realistic assumption all year round. Clearly, the degree of saturation, especially of such superficial sheets, is subject to considerable seasonal and climatic variation due mostly to the rain infiltration. Time variation of S can reasonably be calculated both theoretically on the basis of a rigorous modelling of the filtration in a non saturated porous media (Alonso et al. [5]) or on the basis of regular field measurements carried out during the course of a year at varying depths.
For this purpose, a method to determine simply and directly the degree of saturation was proposed recently (Montrasio and Goldoni [8]) and so far used for laboratory testing only but about to be adapted for field use.

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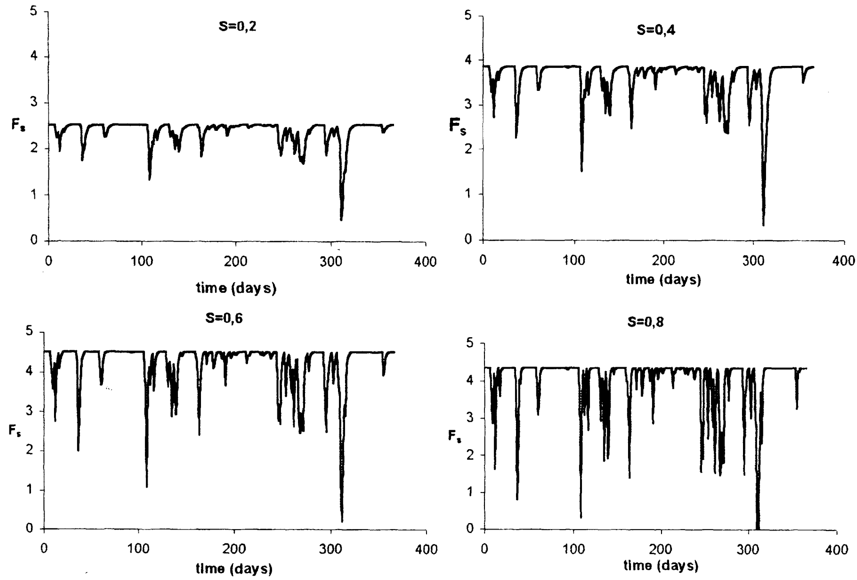

Figure 5: Time variation of the safety factor (for the year 1994) at different degrees of saturation.

As for the dependence of k_t, on F_s (S=0.6), variation of water downflow capacity significantly alters the safety factor, as expected. With k_t,=ca.10^{-5}m/s, instability based on water downflow is to be excluded, whereas with k_t,=ca.10^{-7}m/s instability was observed at several points in time when, in reality, no instability phenomena occurred. A successive analysis allows for the assessment of the value of k_t, at about 10^{-6}m/s.

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As for variation of the safety factor as determined by change in the remaining parameters, it must be stressed that the value of F_s never fell below 1 except at the time of the flood when it dropped below 1 for all values and combinations of the parameters in question, most likely as a result of the considerable effect of rainfall on the safety factor. Finally, it was possible to determine the safety factor of a slope subject to soil-slip during the 1994 flood and undergoing geotechnical laboratory and in situ characterisation that led to the following parameters: β=42°, ϕ=27°, n=0.48, H=1m, G_s=2.7, γ_w=10kN/m^3; α, A and λ values estimated at 3, 100 and 0.4 following previously noted considerations; k_t =10^{-6}m/s and the value of S ranging between a minimum 0.5 and a maximum 0.8 according to an hypothetical seasonal variation. The results are displayed in figure 7 and show that the safety factor for the year 1994 (based on the

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pluviometric diagram, figure 2) was always above 1 with the exception of 5 November when it dropped well below 1.

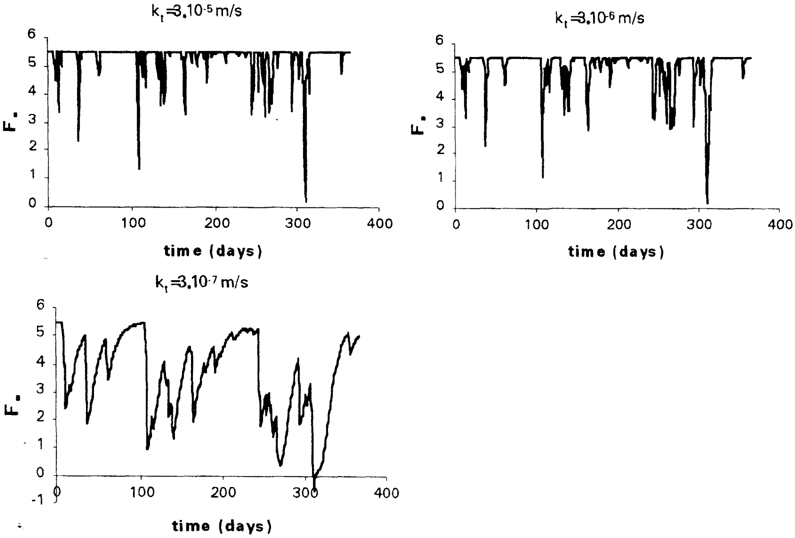

Figure 6: Variation of the safety factor (in 1994) when varying the downflow capacity K_t.

In view of the latter consideration and of the results of parametric analysis, the proposed method of analysis is particularly useful in identifying several crucial aspects of the event under examination. Consequently, attention was devoted on the one hand, to the study of factors most significant in determining the safety factor, and on the other, to the study of the value of parameters not easily calculated on the basis of soil geotechnical characteristics.

7 Conclusions

This paper presented a simplified mechanical model aimed at identifying the onset of superficial plane sliding movements or soil-slips, on the basis of the limiting equilibrium method, shear strength based on soil saturation and a model of water downflow.

The analyses of the safety factor variation by varying a number of characterising factors highlighted two key elements. The first one is the determining role of rainfall and soil water downflow capacity. The second one is the plausible variation of the model parameters based on a typical yearly pluviometric diagram for the area in Piedmont subject to soil-slip during the 1994 flood, led to an accurate forecast of the actual slips and the time of their occurrence.

Therefore, this work will continue in order to possibly find experimental evidence supporting the hypotheses at the basis of this model and to undertake experimental tests on the model's parameters.

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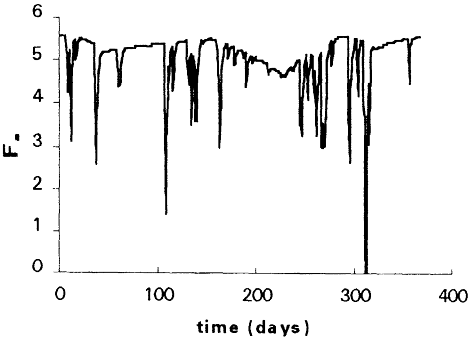

Figure 7: Safety factor variation for the year 1994 in a slope subject to soil-slip during the 1994 flood in Piedmont.

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Section Eight:

Earthquakes