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INFERENCES ON MODELING RAINFALL-INDUCED SHALLOW LANDSLIDES FROM EXPERIMENTAL OBSERVATIONS ON STRATIFIED SOILS

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EXTENDED ABSTRACT

Le frane superficiali indotte da pioggia (quali soil slips o debris-flows) sono una tipologia di movimento franoso che può coinvolgere i primi 2-3 metri di terreno, in genere rappresentato da coltri di alterazione eluvio-colluviali. Tali fenomeni costituiscono un serio rischio per le attività antropiche se si considerano sia le elevate velocità che si possono raggiungere durante la fase di trasporto che gli ingenti volumi di terreno che possono essere mobilizzati per effetto dell'erosione sul fondo del canale. Per questo motivo, negli ultimi anni sono stati dedicati molti sforzi all'elaborazione di tecniche e metodologie funzionali alla predizione spazio-temporale di questi eventi. Tra le nuove metodologie in fase di sviluppo, rivestono particolare importanza i cosiddetti modelli numerici fisicamente basati. Tali modelli tentano di riprodurre i processi fisici che conducono all'instabilità mettendo in relazione pioggia, pressione interstiziale e condizioni di resistenza del terreno. In particolare, molti di questi modelli adottano uno schema di pendio infinito per bilanciare le forze agenti e resistenti sul volume di terreno, usando un modello di infiltrazione per determinare gli effetti della pioggia sulle variazioni di pressione interstiziale. Oltretutto, questo tipo di modelli, tenendo conto della variabilità spaziale dei parametri coinvolti (es: caratteristiche fisico-meccaniche del terreno, intensità di pioggia), possono risultare particolarmente utili per predire l'occorrenza di frane superficiali alla scala di bacino. Tuttavia, l'utilizzo di questi strumenti non sempre consente di risalire alle reali condizioni di innesco, perlopiù a causa della complessità del fenomeno simulato e dell'ingente numero di parametri in esso coinvolto. Tra i vari aspetti che necessitano di essere approfonditi, c'è anche quello del contributo alla stabilità del terreno per effetto della coesione apparente indotta dalla matrice di suzione presente in condizioni non sature. Tale effetto non può non essere preso in considerazione, soprattutto nel caso di terreni caratterizzati da una granulometria limoso-argillosa. Sebbene in letteratura esistano alcuni metodi e formule empiriche per caratterizzare la resistenza di un terreno in condizioni non sature, allo stato attuale sono ben pochi gli studi inerenti l'analisi delle condizioni idraulico-meccaniche basati su osservazioni reali. Da questo punto di vista, alcuni autori hanno evidenziato come la modellazione fisica di laboratorio su modelli di pendio in scala possa rappresentare uno strumento estremamente utile per questa tematica. Tuttavia, solo in pochissimi casi si è tentato di utilizzare i risultati sperimentali per validare e/o migliorare modelli numerici fisicamente basati dedicati alla predizione dell'innesco di frane superficiali alla scala di bacino.

Pertanto, l'obiettivo di questo lavoro è quello di verificare, attraverso prove sperimentali di laboratorio, alcune assunzioni di SLIP (Shallow Landslides Instability Prediction), un modello numerico fisicamente basato finalizzato alla predizione di frane superficiali indotte da pioggia. Nello specifico il modello calcola le condizioni di stabilità, espresse in termini di Fattore di Sicurezza (FS), simulando il processo di saturazione del suolo per effetto di uno specifico input di pioggia e tenendo specificatamente conto del contributo alla resistenza indotto dalla parziale saturazione del terreno per effetto delle piogge antecedenti. Sono stati quindi analizzati i risultati di differenti prove effettuate su un profilo di terreno ricostituito all'interno di una canaletta sperimentale, con l'obiettivo di descrivere e quantificare alcuni aspetti particolari concernenti la modellazione del processo di innesco. Nello specifico, è stata analizzata l'influenza sull'insorgere dell'instabilità dello spessore di due differenti strati presenti all'interno del profilo di terreno, di cui uno dei due caratterizzato da un comportamento coesivo. Per simulare l'effetto della coesione, è stato infatti utilizzato uno strato di sabbia parzialmente saturo, mentre la stessa sabbia (ma in condizioni asciutte) è stata utilizzata per realizzare il secondo strato. Il modello di pendio così costituito è stato sottoposto a differenti tilt tests, e in ciascuna prova è stato variato lo spessore degli strati in modo tale da verificare l'influenza di questo parametro sulle condizioni di stabilità. I risultati ottenuti sono stati quindi utilizzati non solo per corroborare alcune assunzioni del modello, ma anche per verificare la relazione matematica proposta dal modello stesso, e che lega resistenza del terreno e spessore degli strati attraverso il parametro della coesione apparente.

ABSTRACT

In this work, we analyzed the results of different soil laboratory tests performed in a flume test apparatus with the aim to describe and quantify some particular aspects of the modelling of soil slip phenomena. In particular, we analyzed the influence, in terms of slope stability, of the thickness of two strata (a cohesive one and a not cohesive one) composing the slope model. To simulate the presence of cohesion, a partially saturated sand was employed, while the same sand but in dry conditions was used to reproduce the not cohesive stratum. The so-constituted slope laboratory model was then submitted to tilting tests, and in each test the thickness of these layers has been varied in order to investigate the influence of this parameter on slope stability. The obtained results have been used to calibrate several parameters and verify specific assumptions of SLIP, a simplified physically-based and well-tested model for the prediction of shallow landslides occurrence.

Keywords: laboratory flume; triggering model; shallow landslides; physically-based model

INTRODUCTION

Rainfall-induced shallow landslides are processes that occur in numerous natural environments and usually affect the upper meters of soils lying above steep slopes. Considering the high velocity and the large amount of the transported material, such phenomena represent one of the most dangerous geo-hazards worldwide (Reid *et alii*, 2008). For this reason, in the last years great efforts are being made to develop efficient tools for predicting the temporal and spatial occurrence of these events. In this respect, physically-based numerical models (e.g. Montgomery & Dietrich, 1994; Iverson, 2000; Baum *et alii*, 2008; Simoni *et alii*, 2008; Vieira *et alii*, 2010) try to simulate the physical processes leading to instability; however, numerically simulating this kind of phenomena cannot be straightforward, considering the complexity of the triggering process (Greiving *et alii*, 2014). In fact, the material involved in this type of landslides frequently exists in an unsaturated state, therefore an increase in moisture content due to a rainfall event causes a decrease of the apparent cohesion, which represents the contribution to the soil shear strength from the matric suction (Cho & Lee, 2001). If rainfall persists, a progressive saturation from the advancing wetting front leads to the development of a perched water table, that can reduce the effective stress on the potential failure surface to a point where equilibrium can no longer be sustained in the slope (Rao, 1996; Ng & Shi, 1998). However, although there are several methods for characterizing the shear strength of unsaturated soils, and a number of empirical formulas, which make it possible to determine the strength of an unsaturated medium in an approximate way (Zydroń & Dąbrowska, 2012), at present there are still few quantitative studies of hillslope hydrological processes and landslide mechanisms based on real observations (Matsushi *et alii*, 2006). In this sense, different authors (e.g. Eckersley, 1990; Iverson *et alii*, 2000; Wang & Sassa, 2003; Olivares *et alii*, 2009; Ooi *et alii*, 2014) have shown how laboratory-scale physical modelling can be an extremely useful tool to better understand the conditions and mechanisms that precede the failure. However, only in a few cases (e.g. Hungr, 1995; Montrasio *et alii*, 2016) experimental tests have been used to validate and/or improve physically-based models for shallow landslides. Therefore, the aim of this paper is to substantiate several assumptions of SLIP, a simplified physically-based model for the prediction of rainfall-induced shallow landslides (Montrasio, 2000), by means of experimental flume tests. Specifically, the relation between soil strength and thickness of soil layers was analyzed in detail, and a mathematical solution was obtained in terms of apparent cohesion.

MATERIALS AND METHODS

Theoretical basis of SLIP model

The mathematical model

SLIP (Shallow Landslides Instability Prediction) is a mathematical model aimed at predicting the shallow landslide occurrence in response to heavy rainfall events. Assuming an infinite slope, the model performs a stability analysis specifically taking into account the contribution of the partial saturation to the soil shear strength in terms of apparent cohesion ($c\psi^*$) which, in turn, depends on the degree of saturation (Sr) of the soil (Montrasio, 2000). In detail, when the soil is fully saturated the minimum shear strength corresponds to a value of zero matric suction. By reducing the water content within the soil, the shear strength progressively increases until it reaches a peak and then decreases for higher values of matric suction. However, the latter parameter is relatively complicated to determine in practice; although there are other parameters (i.e. liquidity or consistency indexes) that can be used to estimate the shear strength, being a derivative of the moisture content (Matsushi & Matsukura, 2006), SLIP has been properly designed in order to directly express the shear strength as a function of the degree of saturation, considering the relationship between the water content, the degree of saturation and the matric suction. In this respect, Fredlund *et alii* (1996) and Bogaard *et alii* (2014) performed specific experimental tests on different kinds of soils (i.e. medium and fine-grained sands) in order to analyze the relationship between $c\psi^*$ and degree of saturation at confining pressures comparable to those present in the shallow part of the natural soil. Thus, for the calculation of $c\psi^*$ SLIP uses the function which better fits the experimental points (Fig. 1a). This curve, which has a peak whose value depends on the type of soil and corresponds to a degree of saturation approximately equal to 0.7, is given by the following equation:

$$c\psi^* = A \cdot Sr \cdot (1-Sr)^{\lambda} \quad (1)$$

where A (kPa) and λ are model parameters that depend on the soil type. In previous publications (MARI, 2000; MONTRASIO & VALENTINO, 2003; 2007) an estimation of these two parameters for the most common kinds of soil on the Italian territory has been made through a best fitting procedure between the $c\psi^*$ function and the experimental results deriving from a number of suction-controlled triaxial tests.

Another assumption of the model concerns the water infiltration process within the soil in response to a rainfall event. Specifically, the model considers the so-called dual porosity effect (ZHANG & ZHANG, 2009), which consists of a progressive saturation of non-adjacent volumes of soil due to the water infiltration through the soil macro-pores (Fig. 1b). During this process, the saturated portions are characterized by a value of zero apparent cohesion, while the remaining part of the soil maintains a certain value of cψ*, which depends on the initial

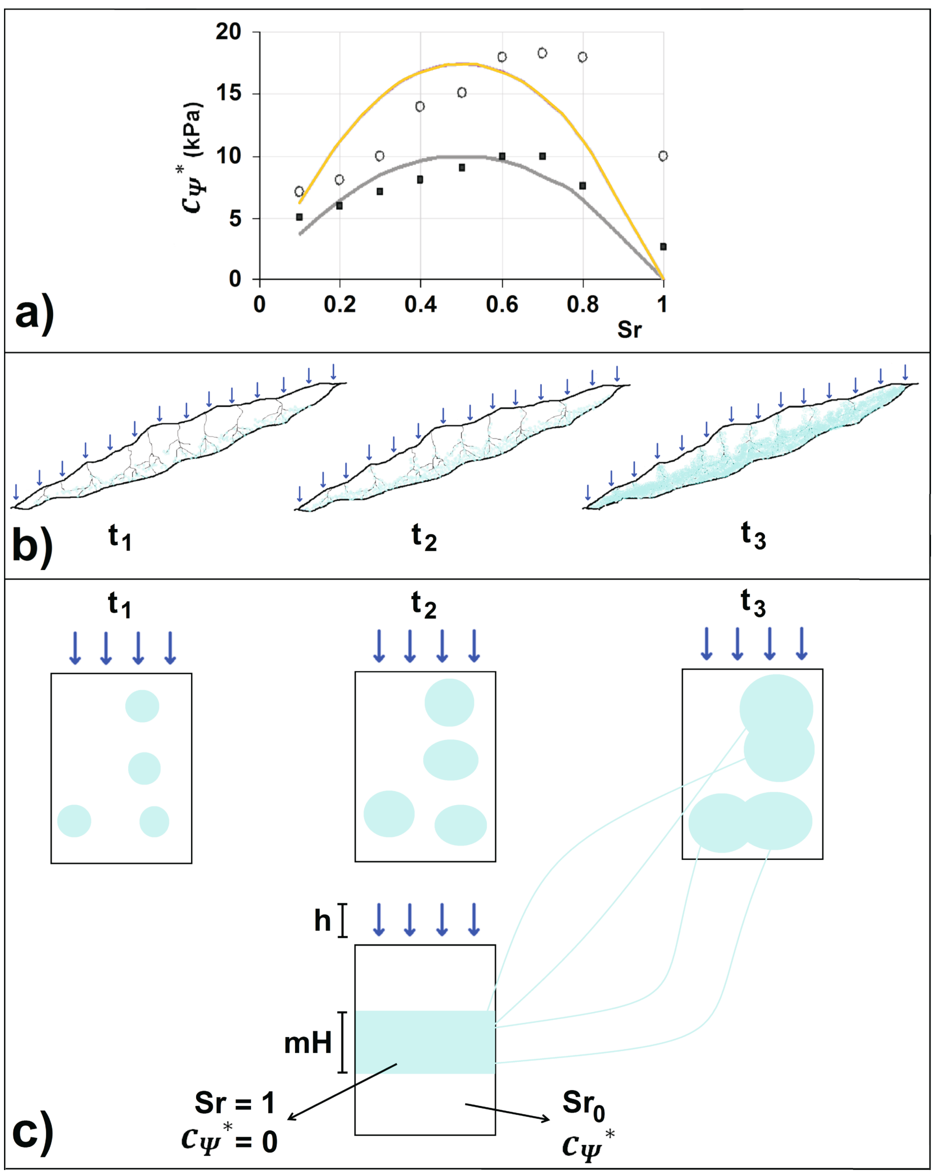


Fig. 1 - Shear strength versus degree of saturation for two soil samples. The symbols indicate the experimental results from FREDLUND et alii (1996), the lines represent the cψ fitting equation; b) From left to right: evolution of saturation process through the soil macro-pores (from MONTRASIO & VALENTINO, 2008); c) From left to right: conceptual sketch of the evolution of saturation process within a soil slice. The last picture in the lower part of the figure represents the main assumption of the hydrological model in SLIP, for which all the saturated portions can be expressed as a single saturated layer of thickness mH*

degree of saturation (Sr_0). The model then hypothesizes that all the saturated portions can be expressed as a single saturated layer (Fig. 1c) whose thickness (*mH*) depends on the rainfall amount according to:

$$mH=h/[n\cdot(1\text{-}Sr)] \qquad (2)$$

where h is the rainfall depth and n is the porosity. However, since the soil slice is composed of an unsaturated ($c\psi^*\neq 0$) and a saturated ($c\psi^*=0$) layer, the model assumes that these two layers can be homogenized in a single stratum having an apparent cohesion, which is a function of the thickness of the saturated stratum:

$$c\psi=c\psi^*\cdot f(m) \qquad (3)$$

where $f(m)$ is the homogenization function that has been defined from the interpretation of the results of the experimental tilt tests presented in this work. From a numerical point of view, the increase of the m parameter after a rainfall event is given by:

$$m_{(increase)}= (\xi\cdot h) / [n\cdot H\cdot(1\text{-}Sr)] \qquad (4)$$

where ξ is a coefficient that quantifies the portion of rainfall amount that does not infiltrate into the soil due to runoff processes. However, the model also takes into account other physical processes that occur in absence of rainfall and cause a decrease of the water amount into the soil, such as evapotranspiration or percolation through the substratum. Consequently, the m parameter decreases according to:

$$m_{(decrease)} = m_0\cdot exp\ (\text{-}K_T\cdot t) \qquad (5)$$

where m_0 is the initial value of the m parameter, t is the time interval and K_T assumes the significance a global drainage capability (its dimension is the inverse of time) which includes not only the hydraulic conductivity, but also the presence of preferential down-flow ways, as previously mentioned. Combining Eq.(4) and Eq.(5), the final formulation of m in time is given by:

$$m_{(t)} = \xi/[(n\cdot H\cdot(1\text{-}Sr)]\ \cdot\textstyle\sum_{i=1}^{\omega} h_i\cdot exp[\text{-}K_T\cdot(t_i\text{-}t_0)] \qquad (6)$$

where h_i and t_i are, respectively, the rainfall depth and time at the *i-th* time interval. Therefore, m is computed at each time step and directly correlates the rainfall depth (h) with the slope stability conditions. Specifically, SLIP applies the limit equilibrium method and, on the basis of the Mohr Coulomb strength criterion, calculates the Safety Factor according to:

$$FS=\{\{cot\beta\cdot tan\varphi'\cdot\ [\Gamma+m\cdot(n_w\text{-}1)]\}+C'\cdot\Omega\}/(\Gamma+m\cdot n_w) \qquad (7)$$

with:

$$\Gamma = [G_s\cdot(1\text{-}n)]+n\ Sr \qquad (8)$$

$$n_w = n\cdot(1\text{-}Sr) \qquad (9)$$

$$\Omega = 2/\ [sin(2\beta)\cdot H\cdot\gamma_w] \qquad (10)$$

where β is the slope angle, φ' is the soil friction angle for effective stress, G_S is the specific gravity of soil solids, γ_W is the unit weight of groundwater and C' is a parameter that represents the total cohesion given by:

$$C' = [c'+c_\psi]\cdot L \qquad (11)$$

where c' is soil cohesion for effective stress, L is the length of soil slice and $c\psi$ is the overall apparent cohesion.

A more detail explanation of the assumptions, fundamental concepts and equation derivation of the SLIP model can be found in previous publications (e.g. Montrasio, 2000; Montrasio & Valentino, 2008; Montrasio *et alii*, 2011; 2012).

The role of homogenization in SLIP model

The triggering of soil slips arises from a very complex interaction between soil and infiltrating water during intense rainfall events. The failure typically involves a very thin superficial stratum of soil that can be considered topsoil or agricultural soil; thus, it is far from the concept of "soil" generally considered in the classical geotechnical engineering for design scopes. However, considering the complexity of such phenomena, the modelling of the triggering process requires a drastic simplification, especially if it is performed at the catchment scale. In this respect, the description of the SLIP model reported in the previous section puts in evidence the simplicity of the model itself, which it is able to take into account the most significant factors affecting the soil slip triggering, in order to properly reproduce the failure process.

One of the main assumptions of SLIP is that the rain infiltrates quickly into the top-soil saturating, in a chaotically way, different soil portions: the overall stability is preserved until the proportion between saturated and partially saturated zones does not exceed a certain value. This physical phenomenon is modeled under the hypothesis of indefinite slope, simplifying the saturated portions (chaotically distributed) in a single saturated layer (whose thickness is easily related with the initial degree of saturation, porosity and unit weight of water), coexisting with the remaining partially saturated portions of slope.

Obviously the presence of the saturated layer causes the deterioration of the overall characteristics of topsoil due to the fact that a partially saturated soil shows higher shear strength than a saturated one (Soranzo *et alii*, 2015). This loose of strength is simulated by SLIP through the homogenization simplified in Eq.(3), where $f(m)$ is the function that describes the degradation of the shear strength characteristics of the partially saturated soil due to the presence of the saturated layer. Such function can be inferred from a series of experimental tilt tests performed on a slope model made up of saturated and partially saturated layers with variable thickness. In the next sections, we will describe in detail the outcome of such tests, that have been performed in an experimental flume apparatus.

Experimental set-up

Experiments are performed in a 100 cm long, 50 cm wide and 30 cm high plexiglass tilting flume. In each test, a soil slope model composed of three different sand layers is placed within the flume, and the flume is tilted until failure occurs (Fig. 2a). In this way, it is possible to simulate a mechanical behavior similar to the one that arises when shallow landslides are triggered.

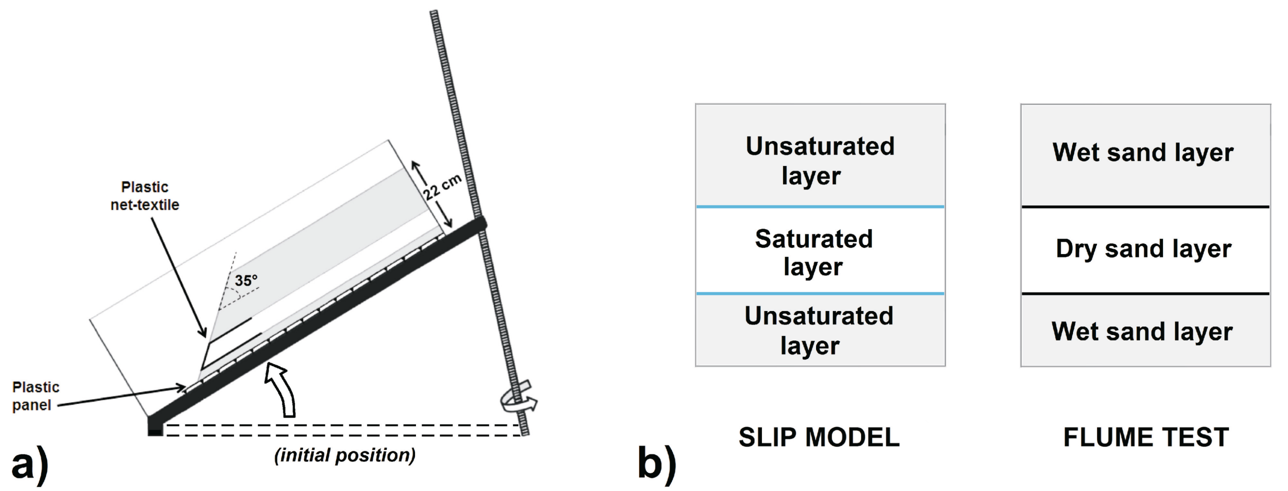


Fig. 2 - a) Scheme of the experimental apparatus; b) Conceptual sketch of the hydrological model in SLIP (left) versus experimental conditions (right)

Specifically, according to the equivalent infinite slope scheme assumed by SLIP, the first and third sand layer, both consisting of wet sand (i.e. *Sr=50%*), represent the impermeable bedrock and the unsaturated portion of the soil, respectively. On the contrary, the second layer is constituted by dry sand and represents the saturated portion of the soil, where the main displacements are expected (Fig. 2b). In this respect, since the behavior at failure of dry cohesionless soils is virtually identical with the behavior at failure of cohesionless saturated soils (Lambe & Whitman, 1969), use was made of dry sand instead of saturated sand, as in the first case it is more feasible to control the boundary conditions during each test. The tested material is a fine carbonate sand (Kenya sand), whose physical and mechanical properties are reported in Table 1. The choice of testing this specific material can be explained considering both its high compressibility, which allows to properly set up the different soil layers, and its fine particle size (Fig. 3), that emphasizes the stabilizing effect due to the partial saturation. In order to evaluate the most appropriate soil geometry, different preliminary tests have been carried out to achieve the least possible disturbance of the slope conditions. The inclination of the frontal wedge has been progressively decreased to 35°, then ensuring that failure occurred within the soil volume and not on the front. During the preparation of the material within the flume, a plastic net-textile was also placed in correspondence of the intermediate layer in order to avoid its collapse, caused by the lack of cohesion of the material. However, it was also necessary to calculate the minimum driving length of the textile. In fact, for high values of tilting, the failure could be caused by the removal of the textile rather than the reaching of the limit equilibrium within the dry sand layer. Therefore, specific preliminary tests have been performed to determine the value of this parameter.

With regard to the preparation of the soil slope model, in each

GRANULOMETRIC CHARACTERISTICS (M.I.T.)	
Coarse sand (%)	0.07
Medium sand (%)	20.88
Fine sand (%)	79.05
PHYSICAL AND MECHANICAL PROPERTIES	
Specific gravity (-)	2.785
Porosity (-) (wet-dry sand layers)	0.5
Degree of saturation (-) (wet sand layers)	0.6
Internal friction angle (°)	35

Tab. 1 - Physical and mechanical properties of the tested material

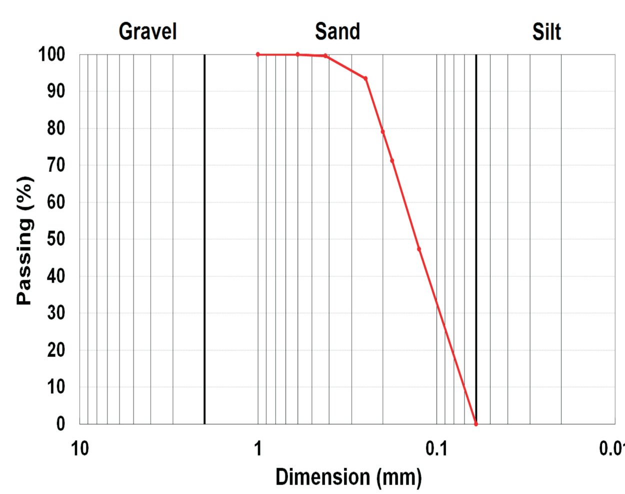
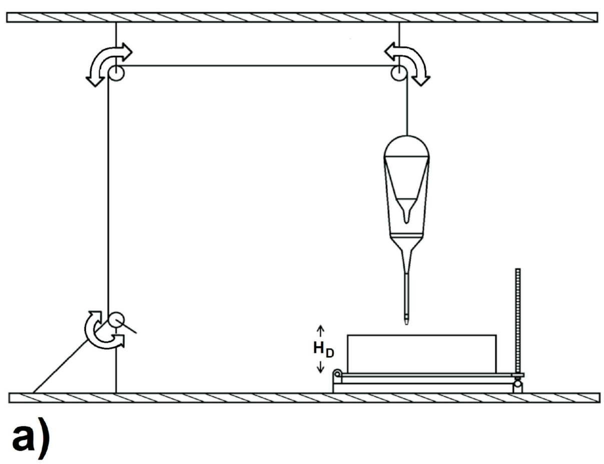


Fig. 3 - Grain size distribution curve for the tested material



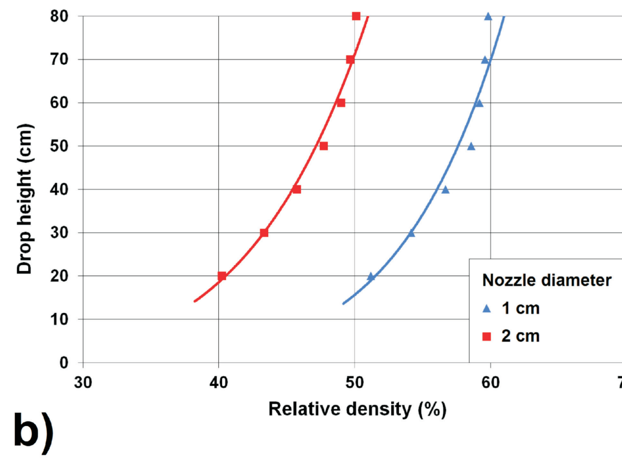


Fig. 4 - Scheme of the dry pluviation system used in this study; b) Relative density versus drop height for two different nozzle diameters

Test	Nozzle diameter (cm)	H_D (cm)	W (kg)	D_R (%)
1	1	20	11.92	51.17
2	1	30	11.99	54.15
3	1	40	12.05	56.68
4	1	50	12.09	58.57
5	1	60	12.11	59.19
6	1	70	12.12	59.60
7	1	80	12.13	59.81
8	2	20	11.67	40.22
9	2	30	11.74	43.33
10	2	40	11.79	45.75
11	2	50	11.84	47.72
12	2	60	11.87	49.02
13	2	70	11.88	49.66
14	2	80	11.89	50.10

Tab. 2 - Drop height (H_D), sand weight (W) and resulting relative density (DR) according to the experimental tests performed with two different nozzle diameters into a known-volume container (i.e. 1.08 x 10^{-2} m^3)

test the first sand layer is compacted until it reaches a thickness equal to 2 cm, while that of the second layer is varied between 0 and 10 cm, adjusting from time to time the third layer in such a way that the total thickness of these two layers is equal to 20 cm. With the aim of assuring the stability of the "bedrock" layer even for the highest slopes, a rough plastic panel is applied to the surface of the flume base. Considering that the larger displacements are expected within the intermediate layer, particular attention is given to control the relative density of this portion of soil for each tilting test. For this reason, the sand was placed into the flume using the dry pluviation method (Fig. 4a). This approach is based on the principle that sand accumulates uniformly on a plane when it drops from a constant height. At first, a known-volume container has been used for the calculation of the relative density of the tested material to changing the height of drop (H_D) and the nozzle diameter (Fig. 4b). On the basis of the results, use was made of the 2-cm nozzle with a height of drop of 80 cm, then imposing a relative density of approximately 50% for all tests (Tab. 2).

EXPERIMENTAL RESULTS AND DISCUSSIONS

Once the design of the experiments has been defined, we evaluated the minimum driving length of the plastic net-textile, required for assuring the initial stability of the dry layer of the soil slope model. Thus, we performed several preliminary tests by keeping the thickness of the intermediate layer equal to 10 cm (i.e. $m = 0.5$) and increasing from time to time the driving length. The selected thickness represents the maximum value reached during the tests, since for higher values it was not possible to assure the initial stability of the model also increasing the driving length of the plastic net-textile placed in the front part of the intermediate layer. In each test, we progressively tilted the flume, paying particular attention to avoid any minimal vibration for the experimental apparatus and checking from time to time the occurrence of possible pre-collapse displacements within the soil. During the tests, it was possible to observe the collapse of the soil slope model as a consequence of the removal of the textile for values of driving length up to 15 cm: above this value, the failure concerns only the upper layer and a portion of the intermediate layer, i.e. a triggering mechanism which clearly reflects the reaching of the limit equilibrium within the dry sand layer. At this point, 12 flume tests have been performed, considering a variable thickness of the intermediate layer and a driving length of the plastic net-textile not lower than 15 cm (Tab. 3). As pointed out by the preceding tests, the collapse is generally extremely rapid and affects only the upper and intermediate soil layer, with no evidences of incipient instability. In just three cases (i.e. Test 1, 7 and 10) we observed minimal displacements before the failure, such as surficial fractures in the upper part of the flume; however, they always occurred near to the critical tilt angle (β_{CR}). If we analyze the relationship between this angle and thickness of the intermediate layer, it results an evident inverse correlation between these two parameters (Fig. 5). In other words, for small values of m, the shear strength is high, whereas it progressively decreases as the thickness increases, tending asymptotically to the internal friction angle value of sand (i.e. 35°). In this sense, the function which best approximates the experimental points is of exponential type:

$$\beta_{CR} = \varphi' + [a \cdot exp(b \cdot m)] \quad (12)$$

where *a* was estimated about 26 and *b* about -5.8.

At this point, in order to define the relationship between m and the apparent cohesion $c\psi$, we considered the entire soil model as a unique material, homogenizing the wet and dry layer in a single stratum. In this way it is possible to calculate, for any value of m, the corresponding value of β_{CR}, and from this, the cψ value. Specifically, on the basis of the assumptions of SLIP model (i.e. infinite slope and Mohr Coulomb strength criterion), we can perform an analysis at the limit equilibrium state:

$$FS=[(W' \cdot cos\beta_{CR} \cdot tan\varphi') + c\psi' \cdot L]/(W' sin\beta_{CR})=1 \quad (13)$$

where:

$$W'=\{[G_s \cdot (1-n)]+[n \cdot S_r \cdot (1-m)]\}\ \gamma_w \cdot L \cdot H \cdot cos\beta_{CR} \quad (14)$$

Then $c\psi$ can be derived from Eq.(13):

$$c\psi=[(1-(tan\varphi'/tan\beta_{CR})]\cdot\{[G_s \cdot (1-n)+n \cdot Sr \cdot (1-m)]\ \gamma_w \cdot H \cdot cos\beta_{CR} \cdot sin\beta_{CR}\} \quad (15)$$

Therefore, as shown in Fig. 6a, Eq.(15) allows to directly relate the apparent cohesion of the homogenized soil profile to the thickness of the "weak" layer that, in this specific case, is composed by dry sand. In this respect it is important to recall that, in the framework of modeling rainfall-induced shallow landslides, the same rationale for the saturated portion of the soil can be used, since effective stresses are being considered (Fig. 2b).

Using the mathematical formulation just described, the apparent cohesion of the partially-saturated layer only (cψ*) has been calculated, in order to define the function f(m) that, according to Eq.(3), relates the apparent cohesion of the single stratum to that of the entire homogenized soil profile (cψ). In this case, the submerged weight of the single soil slice is equal to:

$$W'=\{[G_s \cdot (1-n)]+(n \cdot S_r)\} \cdot \gamma_w \cdot L \cdot H \cdot cos\beta_{CR} \quad (16)$$

and consequently, c_ψ^* can be calculated according to the following equation:

Test	*m* (-)	*mH* (cm)	β_{CR} (°)
1	0	0	61.5
2	0.05	1	55.0
3	0.075	1.5	52.0
4	0.10	2	48.5
5	0.15	3	45.5
6	0.20	4	44.0
7	0.25	5	42.0
8	0.30	6	39.5
9	0.35	7	38.5
10	0.40	8	37.5
11	0.45	9	36.5
12	0.50	10	36.5

Tab. 3 - Critical tilt angles (β_{CR}) resulting from the experimental tests performed with different thickness of the intermediate dry sand layer (mH)

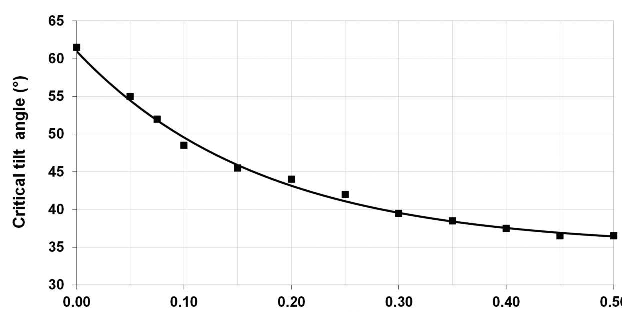


Fig. 5 - Critical tilt angle versus thickness of the intermediate dry sand layer according to the experimental results

$$c_\psi^*=[1-(tan\varphi'/tan\beta_{CR})]\cdot\{[G_s \cdot (1-n)+(n \cdot S_r)]\ \gamma_w \cdot H \cdot cos\beta_{CR} \cdot sin\beta_{CR}\} \quad (17)$$

As can be noted, obviously there is no dependence to m parameter. Thus, we can directly calculate the cψ* value by using the data referred to the testing material (Tab. 1) and considering the critical tilt angle (61.5°) obtained for test n.1, i.e. that performed in absence of the dry sand layer. The resulting apparent cohesion (i.e. 0.863 kN/m^2) can be used to define the ratio $c\psi/c\psi^*$, which is exactly the function that is being tried to define. In other words, by plotting the variation of this ratio as a function of *m*, *f(m)* is the function that best approximates this variation (Fig. 6b). After a series of trials, the fitting function has been obtained and is equal to:

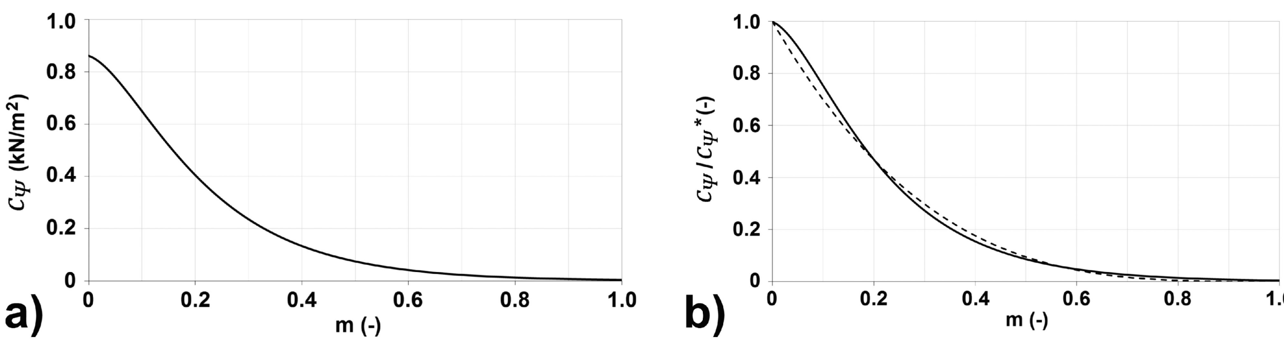


Fig. 6 - a) Apparent cohesion of the homogenized soil profile versus thickness of the "weak" layer, i.e. dry or saturated layer, depending on whether the experimental conditions or the hydrological model in SLIP are being considered, respectively; b) cψ/cψ (i.e. the ratio of the apparent cohesion of the homogenized soil profile to the apparent cohesion of the partially-saturated layer) versus thickness of the "weak" layer. The best fitting function f(m)=(1-m)$^{\alpha}$ is also reported (dotted line)*

$$f(m) = (1-m)^{\alpha} \quad (18)$$

where α is the parameter that gives a non-linear trend to the curve and is equal to 3.4. Thus, the equation which describes the total soil cohesion as assumed by SLIP can be written in this form:

$$C'=(c'+c\psi)\cdot L=\{c'+[c\psi^{*} f(m)]\}\cdot L=\{c'+[A\cdot Sr\cdot(1-Sr)^{\lambda}\cdot(1-m)^{3.4}]\}\cdot L \quad (19)$$

CONCLUSIONS

In this study we have verified some important assumptions of SLIP, a simplified model for the simulation of rainfall-induced shallow landslides, by performing different experimental tilt tests in a flume, in order to reproduce the typical triggering mechanism supposed by SLIP for such phenomena on the basis of field observations. In detail, a soil slope model composed of three sand layers, which represent the bedrock and the saturated-unsaturated layers as assumed by SLIP, has been tilted until failure occurred. We first analyzed the relationship between the critical tilt angle (β_{CR}) and the thickness of the intermediate dry layer: according to the experimental results, it turns out an inverse correlation between these two parameters [Eq.(12)]. Afterwards, since SLIP takes into account the contribution to the soil shear strength due to the partial saturation by assuming an homogenized single stratum composed of an unsaturated and a saturated layer, we first defined the relation between critical tilt angle and apparent cohesion [Eq.(15)]. Afterwards, we obtained the mathematical formulation that relates the apparent cohesion of the homogenized soil slice (c_{ψ}) to that of the partially-saturated layer only (c_{ψ}^{*}) [Eq.(19)].

Therefore, the experimental results substantiate the main assumptions of the proposed model. However, it is important to stress that the specific features of SLIP allow to take into account the most important factors influencing the beginning of the slope movement without the introduction of too many parameters, both in saturated and unsaturated conditions. For this reason, we believe that this model can be considered as particularly suitable for the prediction of the shallow landslide occurrence over large areas, since a detailed knowledge of numerous input parameters is very difficult to acquire at this scale.

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