Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 158 (2016) 476 – 481

Procedia Engineering

www.elsevier.com/locate/procedia

VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING – Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, CNRIG2016

Modelling rainfall-induced shallow landslides at different scales using SLIP - Part I

Lorella Montrasio[a],*, Roberto Valentino[a]

[a]*Università degli Studi di Parma, DICATeA, Viale delle Scienze, Parma 43124, Italy*

Abstract

SLIP (Shallow Landslides Instability Prediction) is a mathematical model developed to foresee the triggering of rainfall-induced shallow landslides (soil slips) and the unstable condition of slopes affected by these phenomena. This physically-based model gives the factor of safety in function of the principal variables influencing the trigger of soil slips: rainfall, geometry, soil state, mechanical and hydraulic characteristics of soil. The specific characteristics of SLIP allowed to use the same means to model the phenomenon from the scale of the representative elementary volume (i.e. flume laboratory tests) to the medium and large scale (regional and national level). This paper (Part I), that is companion of another one published in this Conference (Part II), contains a brief description of the model and focuses on the approach followed in the application of the SLIP model at laboratory scale.

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: Shallow landslides; slope stability analysis; physically-based model; flume test

1. Introduction

The high destructive power and spatio-temporal unpredictability make rainfall-induced shallow landslides particularly dangerous, especially in urban areas, where they often cause significant economic damages [1,2,3,4,5]. Given their main characteristics, such as the widespread localization in consequence of an extensive rainfall event, these phenomena are analysed at medium or large scale. In fact, the type of the adopted method depends on the

---

* Corresponding author.
E-mail address: lorella.montrasio@unipr.it

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016
doi:10.1016/j.proeng.2016.08.475

objective of the analysis. If the aim is a convenient management of emergency plans and a correct planning of mitigation measures against shallow landslides at large scale, different approaches reported in the literature are available at the moment. As an example, for the production of susceptibility maps, statistical methods, such as logistic regression models and artificial neural network, can be used [6,7,8,9]. Since the triggering mechanism of these landslides mainly depends on rainfalls, some of the early-warning systems are based on statistical rainfall-triggering thresholds and take into account both observed and forecasted rainfall data [10,11,12]. These methods allow to get a quick response in a short time, but are extremely simplified and do not consider geological, geotechnical and geomorphological characteristics of the affected area. In order to set up early-warning systems, some authors have applied physically-based slope stability models (SHALSTAB [13], SINMAP [14], TRIGRS [15], GEOtop-FS [16]). These models, together with the wide availability of Geographic Information Systems (GIS), appear suitable to determine both the timing and the localization of landslides, in response to rainfall, on a regional scale. However, as of now, these methods are used to analyse the time-varying landslides susceptibility, but only on small areas and for a short period, due to the great computational effort.

The simplified model named SLIP (Shallow Landslides Instability Prediction) [17,18] falls in the category of the physically-based models. This model allows to take into account, in time, the connection between the stability condition of a slope, the characteristics of the soil, and rainfall amounts, including also previous rainfalls. The SLIP model has been tested through a series of back analyses on a laboratory reduced-scale physical model [19,20]. Moreover, as it will be explained in the companion paper (Part II), SLIP has been applied on single slope scale and on regional scale, i.e. on areas of the order of hundreds square kilometers wide. In the latter case, the accuracy of the model has been evaluated in terms of both space and time, obtaining promising results. The application of the SLIP model to reproduce the phenomenon at different scales will be presented in the following sections and in the companion paper (Part II). The presented methodology allowed from the one hand to strengthen the model assumptions and on the other hand to develop a very “flexible” tool, easily to be used for early-warning purposes.

2. The genesis of the SLIP model

The SLIP model was developed for the first time after the Piedmont flood that caused hundreds of victims and considerable damages in the northern Italian Apennine (Langhe) in November 1994. The model has been then improved several times based on hundreds of field observations. Before describing the main hypotheses of the SLIP model, it is worth defining the soil conditions and processes that cause slope failure during a rainy event, as follows:

1. Soil slip occurs in thin superficial cover (maximum thickness of 1-1.5 m) that is different from soil as commonly intended in geotechnical engineering in many respects, especially its hydraulic characteristics. This type of soil, which is commonly removed during the construction of buildings, contains numerous pores, channels and fissures that are created by several processes, including small animals and shrinkage-drying cycles. These structures form two preferential pathways for the infiltration of rain into the soil: through the pores in the soil matrix and through the macro-porosity. The latter is considered to be prevalent in the SLIP model, while the former is neglected. These infiltration characteristics are considered to be similar for all kinds of soils.
2. The slope is initially stable due, in part, to the contribution of the partial saturation of the soil to its shear strength. The rain infiltrates through the macro-pores much more quickly than through the micro-pores, thus creating saturated, chaotically distributed volumes (saturated zones). The dimensions of these volumes increase due to rain infiltration. This results in a loss of shear strength of the partially saturated soil due to the presence of the saturated zones and a decrease of the stability of the slope. The expansion of the saturated zones continues until their number, distribution and dimensions make the slope unstable.
3. The geometric characteristics of hundreds of unstable slopes observed in the field in recent years indicate that slopes can be considered to be infinite for the purposes of stability analyses.

3. The SLIP model

SLIP was developed to predict the triggering of instability by modelling the principle and most important characteristics of the failure process without including too many elements of the complex mechanism. The use of too many parameters could limit the application of the model at the large scale.

The model defines the safety factor Fs by applying the limit equilibrium method to an equivalent infinite slope that is composed of two soil parts: a partially saturated part and another that represents the saturated zones. Homogenisation is used to obtain the downgraded (with respect to the original conditions) shear strength characteristics of an equivalent soil that is stable in the presence of both saturated and partially saturated zones; this is consistent with both the principles of soil mechanics and the application of the limit equilibrium method.

For simplicity, the saturated zones are represented in the model by a saturated sub-layer of thickness *m*H ($0 < m < 1$). This sub-layer (*m*H) should be put in an unknown position inside the potentially unstable layer (H) but is located at the base of the layer because this choice does not change the consistency of the approach and avoids adding an insignificant parameter, i.e., the location of the saturated sub-layer. This assumption does not affect the rigor of the approach and the saturated sub-layer *m*H co-exists with an unsaturated sub-layer of thickness H(1-*m*) (Fig. 1a). The parameter *m*H is related to the total amount of rainwater, *h*, as follows:

$$mH = \frac{\beta^{*} h}{n(1 - S_r)} \tag{1}$$

where *h* is the rainfall depth given by pluviometric diagrams as a function of time, H is the thickness of the superficial soil that is potentially involved in soil slip, β* is the percentage of rain that infiltrates into the soil, *n* is the porosity, and S_r is the degree of saturation.

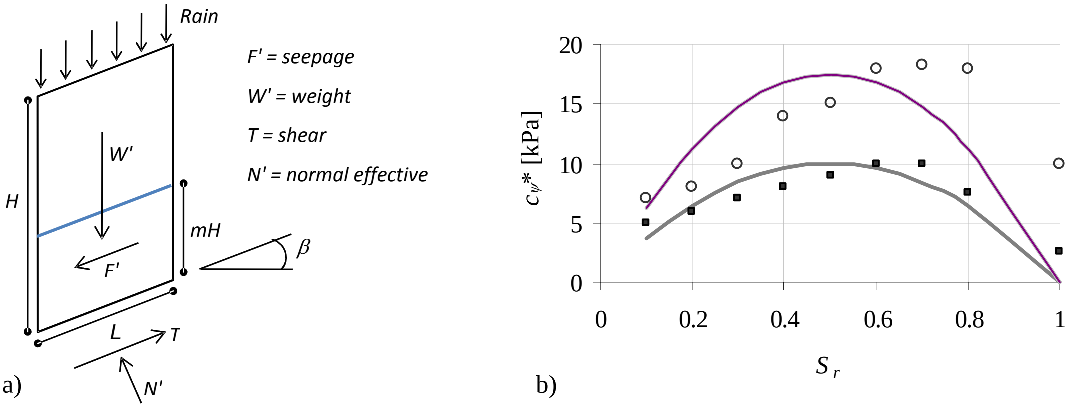

Fig. 1. (a) Slice sketch of the infinite slope; (b) Shear strength versus degree of saturation for two soil samples [18].

The shear strength of the saturated layer is described by the Mohr-Coulomb criterion: $\tau = \sigma' \tan\phi' + c'$.

The shear strength of the unsaturated soil is described by the simplified extended Mohr-Coulomb criterion for unsaturated soils:

$$\tau_{ff} = c' + (\sigma_f - u)_f \tan\phi' + (u_a - u_w) \tan\phi^n \tag{2}$$

where $\sigma' = (\sigma_f - u)_f$ is the normal effective stress on the failure plane at failure, $(u_a - u_w)$ is the matric suction, c' is the effective cohesion, φ' the shear strength angle, and ϕ^n is the friction angle associated with the matric suction stress state variable. The quantity $(u_a - u_w)\cdot\tan\phi^n$ is independent with respect to σ', and in Equation (2) it assumes the meaning of an "apparent cohesion" [21], which is named c_ψ. So the final shear strength criterion can be expressed in a simplified way as follows:

$$\tau = c' + \sigma' \tan\phi' + c_\psi \tag{3}$$

In Equation (3), c_ψ is expressed in terms of matric suction, but in the model SLIP it was preferred to put in relation c_ψ with the degree of saturation S_r instead of matric suction. This choice allows to a better control of the uncertainties on the evaluation of the soil state parameters, due to their range of variation that is much smaller for S_r than for the matric suction. The link between c_ψ and the degree of saturation S_r is obtained by elaborating the experimental results of tests on different kinds of soils [22], such as medium- and fine-grained sands (Fig. 1b). By neglecting the dependence of the relationship between matric suction and volumetric water content on the type of cycle (wetting/drying), the expression of $\underline{\underline{c}}_\psi$ in function of S_r can be written as follows:

$$\underline{\underline{c}}_\psi = A\, S_r\, (1 - S_r)^\lambda \tag{4}$$

where A is a model parameter, that depends on the type of soil, while λ can be considered constant for a wide range of soils. Finally, focusing on the apparent cohesion of the homogenized equivalent slope, c_ψ, it depends on both $\underline{\underline{c}}_\psi$ and the thickness *m*H of the saturated layer. Its expression was obtained by carrying out a series of experimental tests on stratified soil in a flume [19,20] and is given by:

$$c_\psi = \underline{\underline{c}}_\psi\, (1 - m)^\alpha \tag{5}$$

The safety factor is dependent on time because of the decrease of S_r due to the decrease in the number and dimensions of the saturated zones, as well the change in their distribution, caused by evapo-transpiration, downflow and percolation. This is simplified and represented in the model by the decrease of *m* with time, which is obtained using a simple negative exponential function of time:

$$m(t) = m_0 \cdot \exp(-k_t \cdot t) \tag{6}$$

where k_t represents the global drainage capability of the slope that takes into account all the factors mentioned above: evapo-transpiration, downflow and percolation. Its value was derived from back-analysis of a great number of soil slips occurred on different kind of soils.

Finally, the use of the limit equilibrium method leads to obtain the safety factor F_S as follows:

$$\left\{ \begin{array}{lll} F_S = \dfrac{\cot\beta \cdot \tan\phi' \cdot \left[\Gamma + m\left(n_w - 1\right)\right] + C' \cdot \Omega}{\Gamma + m \cdot n_w} & \Gamma = G_S \cdot (1-n) + n \cdot S_r & C' = (c' + c_\psi) \cdot L \\ m = \dfrac{\beta^*}{nH(1-S_r)} \cdot \sum_{i=1}^{\omega} h_i \cdot \exp\left[-k_t (t - t_i)\right] & n_w = n \cdot (1 - S_r) & \Omega = \dfrac{2}{\sin 2\beta \cdot H \cdot \gamma_w} \end{array} \right. \tag{7}$$

The slope instability occurs when F_S reaches a value equal to 1. F_S is function of: the geometrical factors (β, H), the state of the soil (G_S, n, S_r), the soil shear strength parameters in saturated conditions (ϕ', c'), the shear strength in unsaturated conditions (A, λ), a model parameter linked to the simplified modelling (α), the drainage capability of the slope (k_t), the water unit weight (γ_w) and the rainfall depth (h).

4. Application of the SLIP model at different scales

In order to evaluate the effectiveness and reliability of the SLIP model, it has been applied at different scales: at laboratory scale, by considering a representative elementary volume of soil in flume tests, at field scale, by considering the stability of a single slope, and at medium-large scale (regional and national scale). As it will be explained in the following, the lab scale was particularly useful to calibrate the model and to determine the value of some model parameters. Field and medium-large scale applications regarded the comparison between the model outputs and really occurred events. Before describing these applications, only few remarks are needed to understand the adopted approach.

At field scale the approach to evaluate the model parameters and to derive F_S is different depending on the size of the studied area. At the single slope scale the model parameters are obtained by the geotechnical characterization of the soil (lab and in situ tests) and F_S is a deterministic value that unequivocally defines the instant of collapse when $F_S=1$. Instead, at medium-large scale the parameters need to be linked to the geological, lithological and slope information and F_S is defined in reference areas of fixed dimensions (the same of the Digital Elevation Model - DEM). The meaning of collapse is linked to the "probability" that the phenomena can occur. The complete foreseeing needs further methods for the aggregation. In this case, the output of the model can be represented either as F_S maps, which give the value of F_S for each elementary cell with the same DEM resolution (non-aggregated results), or instability index maps (aggregated results), considering larger reference areas. As will be explained in the companion paper (Part II), the instability index is defined as the ratio between the number of elementary cells where $F_S \leq 1$ (instability condition) and the total number of cells in each reference area.

4.1. Flume tests

Physical modelling is an extremely useful tool for the study of the triggering process of shallow landslides. For this reason, numerous laboratory tests have been performed using a flume test apparatus, with a volume of soil of 0.5x0.75x0.12m subjected to an artificial rainfall. A wide range of initial soil conditions (i.e. porosity and water content) has been investigated to analyse the induced effect on failure time and mode. Two main series of flume tests have been carried out. In the first series, no. 18 flume tests were performed on a pyroclastic sand coming from Cervinara (Southern Italy) in order to reproduce the landslide event occurred in that site on December 15, 1999 [19]. During these tests, matric suction and pore pressure were measured in different points of the soil specimen and specific triggering conditions were identified. In the second series, no. 29 tests have been carried out, even simulating the presence of preferential flow directions within the soil [20]. These tests aimed also at reproducing, on a laboratory scale, the landslide event occurred on October 1, 2009, at Giampilieri (north-eastern Sicily) where the testing material had been sampled.

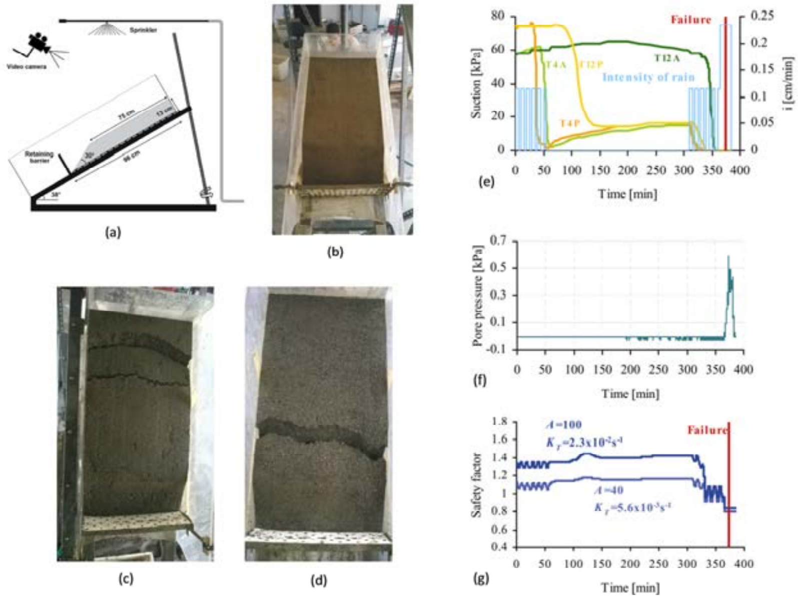

Fig. 2. Flume tests: (a) Laboratory apparatus [19,20]; (b) Soil sample representing the reduced-scale physical model [19,20]; (c) and (d) Different kinds of soil failure after the artificial rainfall [20]; (e) Rainfall depth and suction measurements [19]: tensioneters T4A and T4P where positioned at a depth of 4cm from the soil surface, on the front (A) and on the rear (P) of the soil sample, respectively; tensioneters T12A and T12P where positioned at a depth of 12cm from the soil surface, near the flume bed, on the front (A) and on the rear (P) of the soil sample, respectively; (f) pore pressure measured at the base of the soil sample, near the flume bed [19]; (g) calculated safety factor vs time and parametric analysis [19].

The experimental results obtained from both series of flume tests have been employed to verify the capability of the SLIP model to predict the failure occurrence and to reproduce the triggering process. The main benchmark parameter was the time of failure. To this purpose, all the input parameters had been selected on the basis of preliminary laboratory tests. After the calibration process, the selected input parameters had been maintained constant to simulate the further blind tests. The results obtained from the application of the SLIP model showed that it is able to predict with a good approximation the triggering time of all the performed tests.

Conclusions

The most interesting aspects of the adopted methodology at laboratory scale are:

1. The definition of a physically-based time-varying safety factor based on the comparison between laboratory measurements and results of the SLIP model;
2. The possibility of detect the physical conditions leading to the triggering mechanism;
3. The possibility of modifying, validating and strengthening the hypotheses at the base of the SLIP model.

References

[1] S.D. Ellen, R.W. Fleming, Mobilization of debris flow from soil slips San Francisco Bay Region California, in: J.E. Costa, G.F. Wieczorek (Eds.), Debris flow/avalanches: process, recognition, and mitigation. Reviews in Engineering Geology, vol 7. Geological Society of America, Boulder, (1987) 31-40.

[2] K. Sassa, Recent urban landslide disasters in Japan and their mechanisms, in: Proceedings of 2nd International Conference on Environmental Management. 1 (1998) 47-58.

[3] O. Hungr, Rainfall-triggered shallow landslides and debris avalanches: mechanism and susceptibility mapping. The First Italian Workshop on Landslides, Napoli 8-10 June 2009. 1 (2009) 72-80.

[4] G. Crosta, P. Dal Negro, P. Frattini, Soil slips and debris flows on terraced slopes, Nat. Hazards Earth. Syst. Sci. 3 (2003) 31-42.

[5] F. Guzzetti, C.P. Stark, P. Salvati, Evaluation of Flood and Landslide Risk to the Population of Italy, Envir. Managem., 36(1) (2005) 15-36.

[6] A. Carrara, M. Cardinali, R. Detti, F. Guzzetti, V. Pasqui, P. Reichenbach, GIS techniques and statistical models in evaluating landslide hazard, Earth Surf . Proc. Land. 16(5) (1991) 427-445.

[7] L. Ermini, F. Catani, N. Casagli, Artificial Neural Networks applied to landslide susceptibility assessment, Geomorphology 66 (2004) 327-343.

[8] F. Cervi, M. Berti, L. Borgatti, F. Ronchetti, F. Manenti, A. Corsini, Comparing predictive capability of statistical and deterministic methods for landslides susceptibility mapping: a case study in the northern Apennines (Reggio Emilia Province), Landslides 7(4) (2010) 433-444.

[9] J. von Ruette, A. Papritz, P. Lehmann, C. Rickli, D. Or, Spatial statistical modeling of shallow landslides—Validating predictions for different landslide inventories and rainfall events, Geomorphology 133 (2011) 11-22.

[10] F. Guzzetti, S. Peruccacci, M. Rossi, C.P. Stark, The rainfall intensity-duration control of shallow landslides and debris flows: an update, Landslides 5 (2008) 3-17.

[11] S. Peruccacci, M.T. Brunetti, S. Luciani, C. Vennari, F. Guzzetti, Lithological and seasonal control on rainfall thresholds for the possible initiation of landslides in central Italy, Geomorphology 139-140 (2012) 79-90.

[12] D.K. Keefer, R.C. Wilson, R.K. Mark, E.E. Brabb, W.M. Brown, S.D. Ellen, E.L. Harp, G.F. Wieczorek, C.S. Alger, R.S. Zatkin, Real-time landslide warning during heavy rainfall, Science, 238 (1987) 921-925.

[13] D.R. Montgomery, W.E. Dietrich, A physically based model for the topographic control of shallow landsliding, Water Res. Res. 30 (1994) 1153-1171.

[14] R.T. Pack, D.G. Tarboton, C.G. Goodwin, SINMAP—a stability index approach to terrain stability hazard mapping. SZ Terratech, Salmon Arm, 1999.

[15] R.L. Baum, W.Z. Savage, J.W. Godt, TRIGRS - A FORTRAN program for transient rainfall infiltration and grid-based regional slope stability analysis, version 2.0. U.S. Geological Survey Open-File Report 2008-1159, 2008, 75 p.

[16] S. Simoni, F. Zanotti, G. Bertoldi, R. Rigon, Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS, Hydrol. Processes 22(4) (2008).

[17] L. Montrasio, Stability analysis of soil slip, in: Brebbia C.A. (Ed.). Proc. Int. Conf. Risk 2000, Wit Press, Southampton, 2000, pp. 357-366.

[18] L. Montrasio, R. Valentino, A model for triggering mechanisms of shallow landslides, Nat. Hazards Earth Syst . Sci. 8 (2008) 1149-1159.

[19] L. Montrasio, R. Valentino, Experimental analysis and modelling of shallow landslides, Landslides 4 (2007) 291-296.

[20] L. Montrasio, L. Schilirò, A. Terrone, Physical and numerical modelling of shallow landslides, Landslides (doi 10.1007/s10346-015-0642-x), First online: 02 October 2015.

[21] D.G. Fredlund, H. Rahardjo, Soil Mechanics for unsaturated soils, John Wiley & Sons, 1993.

[22] D.G. Fredlund, A. Xing, M.D. Fredlund, S.L. Barbour, The relationship of the unsaturated soil shear strength to the soil-water characteristic curve, Can. Geotech. J. 33-3 (1996) 440-448.