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The Effects of Various Factors on Slope Stability

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Abstract- A landslide starts as consequence of terrain instability, and for this reason it is important in geotechnical practice to ascertain the stability conditions of soils or rocks. Owing to the significance in the prevention of disasters, slope stability has been the subject of much effort. There exist numerous numerical models, textbooks, and computer programs for assessing the stability on different kinds of terrain. Here the problems of instability and the initiation phase of a landslide are very briefly considered, limiting ourselves to only a few basic concepts. This article starts with the basic laws of friction and cohesion, of fundamental importance not only for the problems of slope stability, but also for the dynamics of landslides.

Keywords- *landslide, slope stability, rainfall, layered soil slopes, Soil-Plant System*

I. INTRODUCTION

Every solid or liquid mass on Earth is influenced by gravity. A mass of soil or rock remains stable if the gravity force is counterbalanced by the reaction forces exerted by the adjacent bodies and the terrain. Rock masses and soils on the surface of the Earth appear steady at first sight. However, this impression is often deceiving, as the masses may slowly creep, terminating with a sudden collapse. Natural buttressing of a potential landslide may be removed of weakened, causing portions of the mass to fall. Change in stability conditions may be consequent to a variety of causes such as river undercutting or ice melting. Earthquakes can instantly change the local force equilibrium, anticipating the fall. The process of mountain building continuously overloads rock masses with renewed stress throughout time scales of several million years. Newly produced deposits may also become unstable. For example, volcanic eruptions deposit enormous amounts of pyroclastic materials, which may subsequently be mobilized by rain.

II. THE EFFECTS OF VARIOUS FACTORS ON SLOPE STABILITY

Gravity would tend to flatten out slopes, if it was not for the cohesion and friction forces of rocks and soils. However, the stability conditions may change due to temporary adjustments of equilibrium or because of external perturbations. In this case, a landslide may be triggered. There are numerous books and articles on slope stability. Here only a few basic examples are discussed to illustrate stability problems without any pretence of completeness. The stability of a slope depends on several factors:

1. The kind of material involved. For example, recent volcaniclastic material may become very unstable and collapse into debris flows and lahars following intense precipitation. In contrast, a hard and compact rock like intact gneiss is normally very stable.

2. The geometry of the material. Layers of rocks dipping toward slope are particularly unstable (Fig. 1). The slope angle is another important variable. The kiasar landslide in iran was probably due to instability along a bedding plane.

Figure 1. A rock overhang unsupported at the base is an unstable condition that may lead to the detachment of portions of rock.

3. The distribution of weight along slope. Loading the top of a slope may have great influence on stability. Likewise, cutting the slope at its base diminishes the buttressing of the lower layers underneath and promotes sliding conditions.

4. Water is one of the most important instability factors. It decreases cohesion in soils and increases weight and pore water pressure in granular media. The rate at which water seeps into to the slope may also be critical. Some slopes may become unstable if even small amounts of water penetrate fast; others are more sensitive to the amount of water fallen in a long time

span. More dramatic are the rapid flows that take place in many areas of the world where rock is blanketed by a thick layer of soil. Following intense rain, several landslides may be created at once, forming a characteristic barren landscape, like in the San Francisco area in 1982, or in the Sarno region in southern Italy in 1997 and 1998.

5. External impulsive forces such as earthquakes, waves, and volcanic eruptions. In July 1888, a swarm of strong earthquakes shook Mount Bandai, in Japan. A series of volcanic explosions, partly phreatic, destabilized a large portion of the summit, which collapsed in a debris avalanche covering an area of 3.5 km2. Better known is the eruption of the St. Helens of March 1980. A flank of the volcanic edifice slowly bulged during the 1980 activity following more than a century of dormancy. The progressive deformation finally resulted in a giant collapse and a debris avalanche with approximate run-out of 30 km. Following the landslide, the pressure underneath the northern sector of the edifice plummeted, which caused the strong blast recorded in the photographs.

6. Vegetation may influence stability through mechanical cohesion and removal of water via evapotranspiration.

III. FACTOR OF SAFETY

To quantitatively assess the stability of a slope in engineering geology, a parameter F known as factor of safety is introduced. The factor of safety is the ratio between the resistive forces and gravity pull

$$\textit{Factor of safety} = \frac{\textit{Resistance forces}}{\textit{Gravity force parallel to slope}}$$

In the assessment of slopes, engineers primarily use factor of safety values to determine how close or far slopes are from failure. When this ratio is greater than 1, resistive shear strength is greater than driving shear stress and the slope is considered stable. When this ratio is close to 1, shear strength is nearly equal to shear stress and the slope is close to failure, if FS is less than 1 the slope should have already failed. However some of slope instability will be discussed.

A. safety factor for slopes under rainfall action

Infiltration processes in a horizontally stratified and vertically fractured soil layer of a fine-grained pyroclastic soil overlying a more permeable pumiceous layer have been modeled for different rainfall scenarios by a finite elements dual-permeability model (Galeandro et al. 2011, 2013b). The water flow infiltration in the soil matrix is described using the two-dimensional Richards equation, while soil hydraulic properties are described using the van Genuchten (1980) and Mualem (1976) relationships. When the rainfall intensity exceeds the infiltration capacity of the matrix, a certain amount of water is not able to infiltrate into the matrix and starts flowing into fractures. Infiltration flow in fractures is modeled using the continuity equation. The flow rate in the fractures is obtained, at different depths, as the difference between the fracture inflow rate and the amount of water laterally adsorbed by the matrix, which depends on the amount of water available in the fractures and on the saturated hydraulic conductivity of the soil matrix (Fig. 2a).

Distributions of the degree of saturation and pressure heads were then used in the stability analysis of a hill slope

with the above-described stratigraphic sequence. The adoption of these results for the stability evaluations of steep hill slopes is not formally correct, since the infiltration model works, so far, only for horizontal soil layers.

However, the main purpose of this work was to underline the potential influence of the fractures and the capillary barrier on the infiltration process and on the slope stability. Depending on different rainfall scenarios, this approximation was considered to be acceptable as a first-level qualitative evaluation of the problem. Evaluations of the hill slope stability have been performed according to the infinite slope model (Fig. 2b).

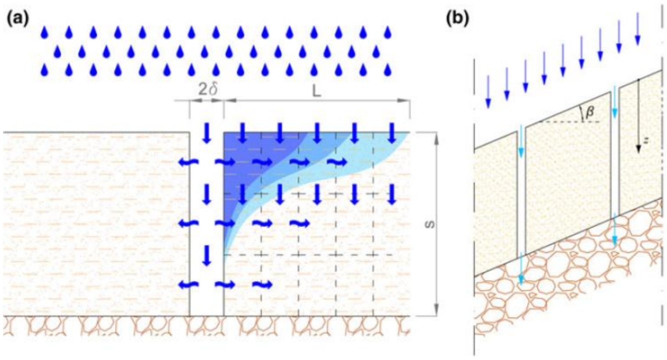

Figure 2. (a) Schematic representation of the model and (b) schematic representation of the hill slope (after Galeandro et al. 2013b)

Thus, there are many methods of evaluating safety factor for slopes under rainfall action, which include the following:

B. Limit equilibrium methods

Those methods are usually analyzed by discretizing the mass of the failure slope into smaller slices and treating each individual slice as a unique sliding block. All limit equilibrium methods of slope stability analysis divide a slide-mass into n smaller slices, as shown in Fig.3. Each slice is affected by a general system of forces, as shown in Fig. 3. Three methods, which are based mainly on methods of slices, are used.

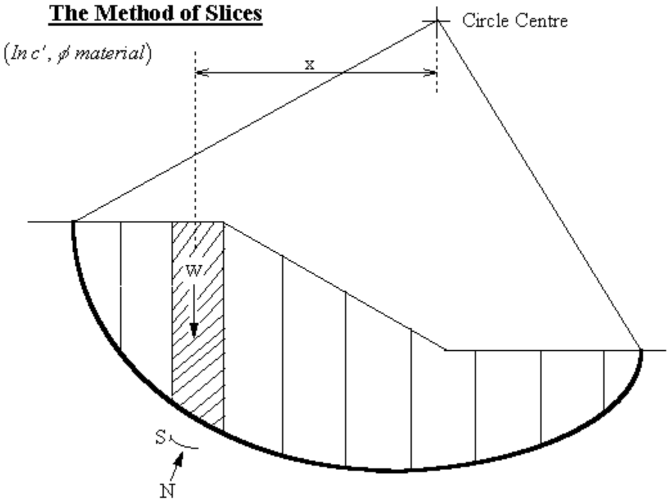

Figure 3. Division of potential sliding mass into slices.

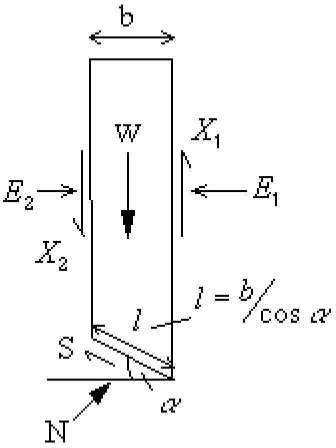

Figure 4. Forces acting on each slice

C. *Simplified Bishop Method*

This method satisfies vertical force equilibrium for each slice and overall moment equilibrium about the center of the circular trial surface. The simplified Bishop method also assumes zero inter slice shear forces. Thus, Bishop's method could be used to compute a factor of safety (F.S) =F for noncircular surfaces, where FOS is factor of safety= ''F'' and can be calculated as follows:

$$\mathrm{F.S} = \frac{1}{\sum \mathrm{W}\sin(\alpha)} \sum \left[\frac{c\,\beta + \mathrm{W}\tan(\phi) - \dfrac{c\,\beta}{\mathrm{FS}}\sin(\alpha)\tan(\phi)}{\cos(\alpha) + \dfrac{\sin(\alpha)\tan(\phi)}{\mathrm{FS}}} \right] \tag{1}$$

FS is on both sides of the equation as noted above.

D. *Simplified Janbu Method*

The simplified janbu procedure assumes that there are no inter slice shear forces. The geometry of each slice is described by its height, h, measured along its centerline, its width, b, and by the inclinations of its base and top, respectively. Janbu's method satisfies vertical force equilibrium for each slice, as well as overall horizontal force equilibrium for the entire slide mass (i.e., all slices).

E. *Morgenstern-Price Method.*

This method was developed by Morgenstern and Price in 1965 and spencer in 1967 which consider not only the normal and tangential equilibrium but also the moment equilibrium for each slice in circular and non-circular slip surfaces. It is solved for the factor of safety using the summation of forces tangential and normal to the base of a slice and the summation of moments about the center of the base of each slice. The equations were written for a slice of infinitesimal thickness. The force and moment equilibrium equations were combined and a modified Newton-Raphson numerical technique was used to solve for the factor of safety satisfying force and moment equilibrium. The solution required an arbitrary assumption regarding the direction of the resultant of the interslice shear and normal forces.

F. *Fellimens Method*

In this method, landslide type is assumed rotational slip, as shown in Fig. 5. Moreover, landslide soil is divided into some slices in order to calculate moment along the critical circle. Therefore, some parameters shall be calculated as follows: R is radius of critical circle (m); W is weight of each slice (kN); a is angle between horizontal axis and the base of slice (degree); L is length of the base of slice (m); C is Cohesion (kN/m2); and u is angle of shearing resistance (degree). Factor of safety (F) can be estimated by the following formula:

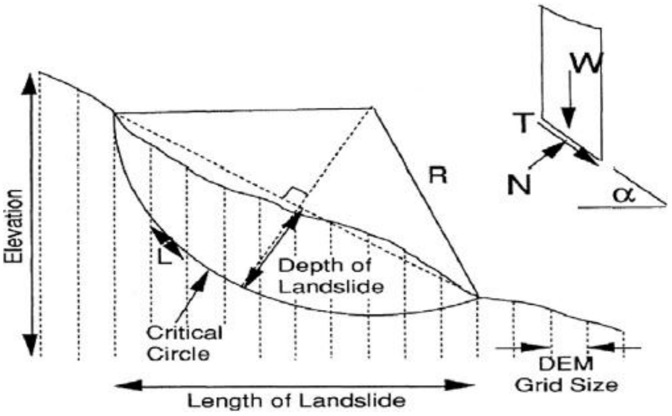

Figure 5. Illustration of Fellenius method.

G. *Stability determination for layered soil slopes*

Evaluation of landslides with different soil layers was done by Simon et al. (2000). Simon et al. (2000) developed a 2-D streambank failure model that allows for a slip plane crossing multiple soil layers with differing friction angle and cohesion. The model worked well in post-diction of failure events along Goodwin Creek, MS, USA.

A simple model of stability analysis consists in analyzing a homogeneous slope like in Fig. 6, including the possible presence of water at a certain depth. The resistive forces deriving from cohesion and friction can be written in the following way;

$$Fres = CwL + (\sigma - PW)\ wL \tan \Phi \qquad (2)$$

Where the effect of water resulting in pore pressure PW has been added. Water tends to destabilize the slope, because as evident from above Equation, it acts in the direction of reducing the contribution of the effective friction angle. The water table is assumed to lie at a constant depth. Because the normal pressure is (Sect. 2.1)

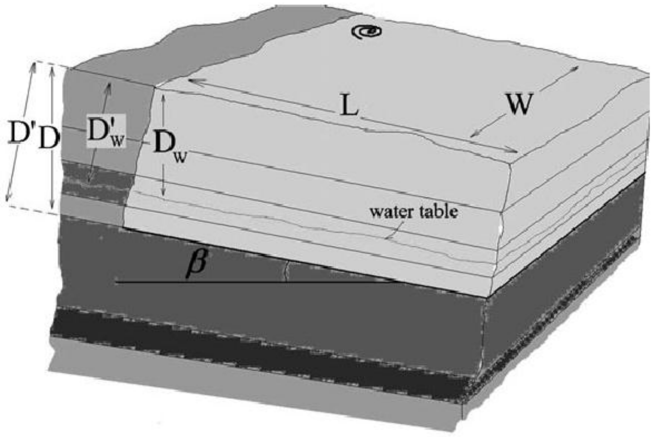

Figure 6. Layered slope for the calculation of the factor of safety FS

$$\sigma = \rho g D \cos 2\beta \qquad (3)$$

$$PW = \rho W g\ (D - DW) \cos 2\beta \qquad (4)$$

It is found that

$$Fres = CwL + (\Delta\rho D - \rho W DW)\ gw\ L \cos 2\beta \tan \Phi \qquad (5)$$

Whereas accounting also for the weight of pore water

$$Fp = [\rho D + \rho W\ \chi\ (D - DW)]\ gw\ L \sin\beta \cos\beta \qquad (6)$$

Where $\chi < 1$ is the volume fraction of water for the case of 100% saturation. Considering that $\rho D >> \rho W\ \chi\ (D-DW)$, this term can be neglected for simple estimates.

H. Mechanical Features of Soil-Plant System

The first studies concerning the impact of vegetation on slope stability were conducted in the 1970s. Laboratory and in situ tests were conducted and analytical models were developed in order to quantitatively assess the mechanical contribution of plant roots to soil strength. The soil reinforcement by plant roots can be compared to reinforced concrete containing steel fibers. Both soil and concrete are strong in compression and weak in tension. Numerous tests were conducted to study the behavior of the soil-root composite system. Most tests were carried out with direct shear devices [Waldron; 1977, Wu et al; 1979, Gray and Ohashi; 1983]. Also Brenner in 1973 conducted tests on an inclined model of the vegetated slope, where both live and dead roots after clear-cutting were used. The pull-out behavior of plant roots was also the subject of numerous investigations [Pollen and Simon; 2005, Pollen ;2007]. The tensile strength of plant roots was shown to be dependent on the root diameter. A threshold diameter exists above which roots are more prone to breakage than pull-out. However, this threshold may change with the soil moisture. In moist soils the friction between root and soil is lower and the threshold diameter for the pull-out resistance increases.

Some pioneer works in the quantitative modelling of root reinforcement were carried out by Wu, Waldron and Wu et al. The Wu model with some latter amendments is very simple and based on a number of approximations. The enhancement of strength by plant roots is considered as an additional cohesion, which is introduced into the Mohr-Coulomb failure criterion. The cohesion is dictated mainly by two factors, namely the average root tensile strength and root area ratio (RAR), which is the ratio of area occupied by roots on a certain plane. The model assumes that all roots are initially perpendicular to the slip surface and break at the same time. The contribution of plant roots to the shear strength is dependent on the angle of shear distortion of the root and can be formulated as follows:

$$s_r = \sigma_r \tan\phi' + \tau_r = t_r(\cos\theta \tan\phi' + \sin\theta) \qquad (7)$$

Where σr and τr are normal and shear stress respectively, Φ is the friction angle of soil, Θ is the angle of shear distortion of the root, tr is the mean traction of plant roots, which is defined by the traction force Tr over the area A

$$t_r = \sum T_{ri}/A \qquad (8)$$

Some test results show that the value of (cosΘ tan Φ′ + sinΘ) can be taken as 1.2 for the distortion angle Θ in the range 48° – 72°. The contribution of plant roots to the shear strength of the soil can be then included into the Mohr-Coulomb failure criterion as follows:

$$s^* = s + s_r = c' + \sigma' \tan\phi' + s_r \qquad (9)$$

Where s and c′ are the shear strength and cohesion of the bare soil respectively.

The above approach is widely used in simulating the strength of soil-root composite. Recently, some improvements are made towards better understanding of the process and more realistic description of the deformation mechanism of the soil-root composite [pollen et al; 2009].

The recent study by Schwarz et al. in 2010 and 2012 showed that the spatial distribution of roots should be taken into account, when considering the reinforcement of the soil with roots. The Root Bundle Model (RBM), proposed by Schwarz is based on the pull-out force – displacement relationship, coupled with the model for lateral root distribution. The RBM, similar to the FBM considers the progressive failure of the roots. The load is apportioned among all the roots by root diameter. RBM allows the estimation of the maximum value of soil reinforcement by plant roots, the root bundle elongation (displacement) as well as the secant Young’s modulus.

Recently, a new approach to characterize the root growth and distribution was proposed by Dupuy et al. in 2010, where a density function is introduced to describe the root structure (Fig. 7).

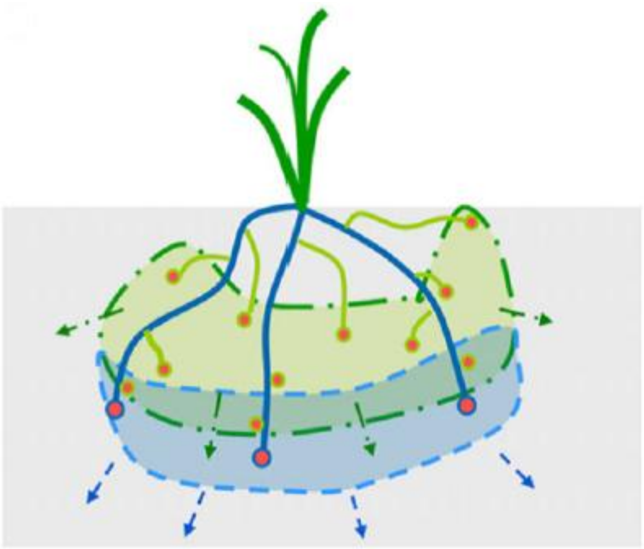

Figure 7. The development of root systems as waves of meristems [Dupuy et al; 2010]

This model allows the description of the relationship between the dynamics of meristem distribution and root architecture. Also this approach has certain advantages over the traditional models. However, the computational time is rather long. Therefore it is mainly restricted to modeling single plant.

IV. CONCLUSION

The purpose of this study is to quantify the influence of various factors in the stability of a slope. Important contributions in this paper are also related with the suggestion of methods to assess the evolution of the resistance forces of the slope, focusing mainly on the evolution of the undrained shear strength. Thus, the following conclusions have been drawn from this study:

1- The method of slices is extremely popular on account of its simplicity in dealing with layered soils, complex slope geometry, and the presence of pore water pressure as well as pseudo static earthquake body forces.

2- the presence of water and rainfall is one of the main reasons for the instability of the slope.

3- Vegetation helps stabilize steep forested slopes chiefly by reinforcing the soil through tree roots and by changing the soil water regime.

4- Pore water pressures within the soil change seasonally in response to precipitation. Soil moisture in areas where the forest has been recently cut is usually greater than in uncut areas.

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