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Reliability analysis of root-reinforced slopes

Analyse de stabilité des pentes renforcées avec de végétation

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ABSTRACT: The use of vegetation is a bio-engineering sustainable measure for shallow landslides risk mitigation and slope erosion control. Root reinforcement can be modelled modifying conveniently the Mohr-Coulomb failure criterion by means of a term, which represents the apparent cohesion related to the root tensile strength and to the spatial distribution of roots inside the soil. In order to verify the plants positive effect on slope stabilization, the authors carried out several slope stability deterministic analyses under seismic conditions, varying slope geometry and using the limit equilibrium methods.
However, due to the inherent uncertainty and variability that characterize both soil and roots, the level of reliability of these bio-engineering techniques has to be investigated. For this purpose, a probabilistic analysis has also been performed by using the Monte Carlo simulation, in order to evaluate the effect of variability in the input design parameters.

RÉSUMÉ: L'utilisation de la végétation est une mesure bio-technique durable pour l'atténuation des risques de glissements de terrain peu profonds et le contrôle de l'érosion des pentes. Le renforcement des racines peut être modélisé en modifiant le critère de rupture de Mohr-Coulomb au moyen d'un terme qui représente la cohésion apparente liée à la résistance à la traction des racines et à la distribution spatiale des racines dans le sol. Afin de vérifier l'effet positif des plantes sur la stabilisation des pentes, les auteurs ont effectué plusieurs analyses déterministes de la stabilité des pentes dans des conditions sismiques, en variant la géométrie des pentes et en utilisant les méthodes d'équilibre limite.
Cependant, en raison de l'incertitude et de la variabilité inhérentes qui caractérisent le sol et les racines, le niveau de fiabilité de ces techniques de bio-ingénierie doit être étudié. À cette fin, une analyse probabiliste a également été réalisée à l'aide de la simulation de Monte Carlo, afin d'évaluer l'effet de la variabilité des paramètres de conception en entrée.

Keywords: Root Reinforcement, Reliability analysis, Slopes, Sustainability, Shallow landslides.

1 INTRODUCTION

Passive control works are used as risk mitigation measures for protection against shallow landslides in order to intercept the flow during its propagation or in the deposition zone (Canelli et al., 2012; Moraci et al., 2015). The use of vegetation represents a risk mitigation measure for preventing the triggering or reactivation of shallow landslides. Specifically, scientific literature (Cazzuffi et al., 2014; Cazzuffi et al., 2016; Dias et al., 2017; Wu, 2013) suggests that roots in soil generally promote an increase in soil shear strength within the rooted thickness due to the mechanical effects of soil-root interaction mechanisms (roots act like anchoring) and to the hydrological reinforcement via evapo-transpiration (volumetric water content decreases while soil suction increases).

Currently, the knowledge necessary to perform a reliable design for this engineering practice is still lacking due to the uncertainties related to soil variability and vegetation, which are very difficult to quantify. For this purpose, a probabilistic slope stability analysis has been carried out in order to evaluate the variability effect in the input design parameters. The aim of the research is to provide the reliability level for root-reinforced slopes designed by using limit equilibrium methods.

2 ROOT REINFORCEMENT

The presence of vegetation (grasses, shrubs and trees) on a slope contributes to the improvement of soil geotechnical characteristics through the action of the roots, being them generally provided with an excellent tensile strength. In addition to root tensile strength, the soil shear strength increasing provided by root reinforcement also depends on the density and distribution of roots within the soil (Waldron, 1977; Wu, 1976).

The assessment of the root reinforcement can be obtained by means of in-situ and laboratory direct shear and triaxial tests (Bovolenta et al., 2018; Mazzuoli et al., 2016; Docker and Hubble, 2008; Giadrossich et al., 2017; Pollen and Simon, 2005) or back-analysis methods (Cislaghi et al., 2017).

The more common approach to model the root reinforcement is to modify the Mohr-Coulomb failure criterion with the introduction of an additional „pseudo-cohesion“, C_r, according to Wu (1976) and Waldron (1977):

$$\tau = c' + \sigma_n' \tan\phi' + C_r \tag{1}$$

Although more complex models have recently been proposed (Cohen et al., 2011; Ekanayake and Phillips, 2002; Schwarz et al., 2010), the Wu (1976) and Waldron (1977) model is still widely used in the common engineering practice for its simplicity. The assumption of the model is considering that the roots start to deform due to the constraint response of friction forces at the soil-root interface when a shear force is applied to the soil, according to the scheme shown in Figure 1.

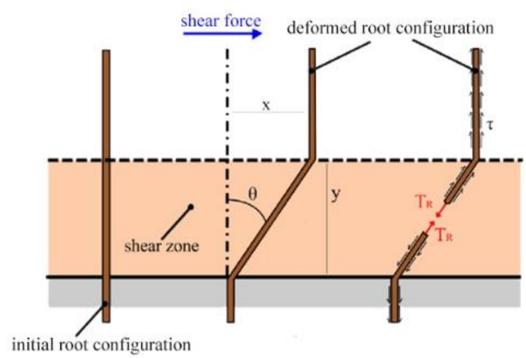


Figure 1. Soil-root interaction model (modified from Wu, 1976; Waldron, 1977)

Roots are assumed as rigid bars, orthogonal to the shear plane; when the sliding starts, the root rigidly rotates in the shear zone (*y*). The rotation θ allows the mobilisation of the root tensile force, T_r, which has two components acting on vertical (F_t, equation 2) and horizontal direction (F_n, equation 3) respectively:

$$F_t = T_r \sin\theta \tag{2}$$

$$F_n = T_r \cos\theta \tag{3}$$

Therefore, the additional strength contribution can be expressed as:

$$C_r = \Delta\tau = t_r \frac{A_r}{A} (\sin\theta + \cos\theta \tan\phi') \tag{4}$$

where ϕ' is the soil shear strength angle; θ is the angle between the deformed root configuration and the initial vertical one and t_r is the mobilised root tensile stress. The root area ratio, A_r/A, represents the spatial distribution of roots (RAR) that is the ratio between the root cross-sectional area (A_r) and the soil cross section (A).

Based on experimental results, Wu (1976) proposed a mean value equal to 1.2 for the term ($sin\theta+cos\theta\ tan\phi'$) in equation (4), since this term is not so much affected by variations in θ e ϕ' angles.

The root tensile stress t_r depends mainly on the plant species and on the diameter and age of the roots (Bischetti et al., 2003). With regard to the single species and according to experimental results of tensile tests, an exponential expression linking the mean diameter of the tested root species (d) to the mobilised tensile stress has been defined (Bischetti et al., 2009; Gray and Sotir, 1996):

$$t_r = \alpha\, d^{-\beta} \tag{5}$$

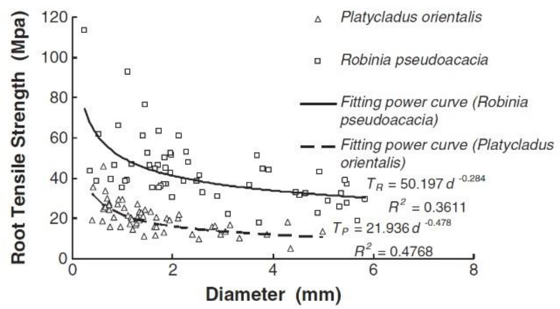
where α and β are empirical parameters depending on species.

3 INPUT PARAMETERS VARIABILITY

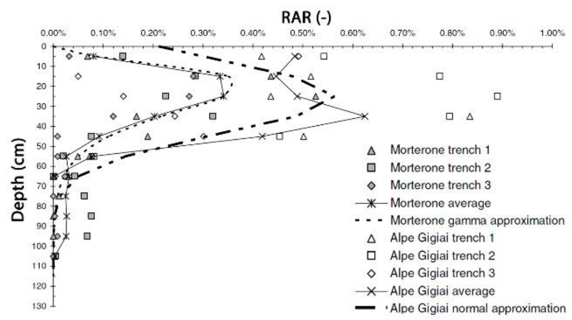
Uncertainties due to the lack in studies about the correct stratigraphy, the difficult determination of soil design parameters (for instance, the in-situ spatial variation cannot be well reproduced as well as many errors can occur during geotechnical tests), and other many important factors may have a significant effect on the stability of a natural slope.

In the specific case of a rooted slope, even the variability of the root parameters must be taken into account. In fact, the strength increment due to the roots, which depends on both the root tensile strength and spatial distribution as previously shown, is highly affected by the uncertainty of these parameters (Figure 2 a, b).

Most of the codes in force took place considering the semi-probabilistic approach, which uses partial factors on loads, resistances and geotechnical parameters in order to create a design parameter value taking into account its own uncertainties. The partial factors are correlated to the probability of failure (or reliability index), therefore the reliability analyses can be a good tool that is capable to evaluate the uncertainties effects on design parameters. Specifically, the reliability analyses allow quantifying the ability of a structure to fulfil the specified requirements, including the design working life for which it has been designed.



(a)



(b)

Figure 2. Uncertainty of root tensile strength values (Ji et al., 2012) (a) and RAR (Bischetti et al., 2005) (b)

During the last decades, the probabilistic approaches and the reliability analyses for slope stability have become quite widespread. In this context, the design parameters are considered as random variables, for which the probability density functions have to be defined. Consequently, also the factor of safety (*FS*) is considered as a random variable with a certain probability distribution. The variability of the design parameters is often quantified by means of the coefficient of variation, *COV*, which is the ratio of the standard deviation to the mean value:

$$COV = \frac{\sigma_x}{\mu_x} \tag{6}$$

These methods provide the percent probability for slopes being unstable; therefore, the probability of failure (or the reliability index) can be used as an indicator for the work performance. Although the probabilistic approach is now widely used, scientific literature and design practice are rather lacking in terms of its application to root-reinforced slopes. In the current research, the variability influence of soil and roots input parameters on slope performance has been investigated, analysing the results in terms of reliability index.

4 ANALYSIS RESULTS

In order to evaluate the positive contribution provided by root reinforcement on slope stabilisation as well as the reliability of this design practice, stability analyses have been carried out for slopes with assigned geometric (slope height *H*, angle of inclination with respect to the horizontal α) and mechanical (soil shear strength angle ϕ', cohesion c', soil unit weight γ) characteristics. The mechanical contribution of roots has been considered introducing the $\Delta\tau$ term (equation 4), while the root geometry has been expressed by the average value of its depth inside the soil, h_r.

Stability analyses under seismic conditions have been performed using the pseudo-static approach ($k_h = 0.11$; $k_v = -0.06$) applied to the simplified Bishop's Method, probably the most popular limit equilibrium method adopted for slope stability analysis that allows searching for the critical slip surface to which the minimum factor of safety matches.

4.1 Deterministic benchmark

Initially, deterministic stability analyses have been carried out for slopes having the characteristics shown in Table 1. The range of the investigated values has been chosen adequately in order to be compatible with granular soil slopes. With regard to $\Delta\tau$, a wide range has been analysed due to the difficulty in its estimation, as it depends on several factors, such as the type and age of plants, site conditions and the position of the shear band. The design approach 1, combination 2 (EC7 - CEN 2004) has been used for the deterministic stability analyses. According to EC7 (CEN 2004), the minimum value of the factor of safety to be achieved is equal to *FS* = 1, that is the limit equilibrium condition.

Figure 3 shows the trend in the factor of safety *FS* for varying strength root contribution $\Delta\tau$ and root height h_r, for slope having $\alpha = 30°$ and $\phi' = 35°$.

Table 1. Root-reinforced slopes characteristics

Slope	**Parameter**
H	10 m
α	30°
ϕ'	35°
c'	0 kPa
γ	20 kN/m^3
Root	**Parameter**
h_r	0.5; 1; 1.5; 2 m
Δτ	5; 10; 15; 20, 30, 40, 50, 60 kPa

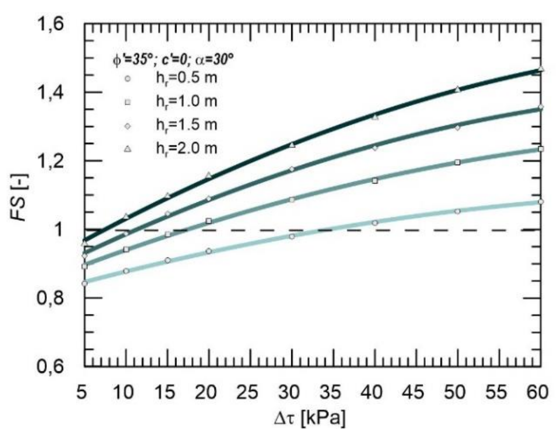


Figure 3. Factor of safety trend for α = 30° and ϕ' = 35°

It is possible to observe that the factor of safety increases with increasing strength root contribution and, $\Delta\tau$ being equal, it increases with increasing root height, as expected. *FS* reaches and exceeds the threshold value (*FS* = 1) when $\Delta\tau$ is higher than about 7 kPa; 11 kPa; 17 kPa and 33 kPa for h_r = 2 m; h_r = 1.5 m; h_r = 1 m and h_r = 0.5 m respectively. Within the range of the investigated $\Delta\tau$ values, the higher *FS* increasing has been obtained for the higher root height. Specifically, ranging from 5 to 60 kPa the increment is equal to 53% for h_r = 2 m; 47% for h_r = 1.5 m; 38% for h_r = 1 m; 28% for h_r = 0.5 m.

4.2 Probabilistic analysis

Following, a probabilistic analysis has been carried out in order to validate the deterministic study from the reliability point of view, i.e. to evaluate whether or not the reliability level is acceptable for slopes having a factor of safety higher than the threshold value. In probabilistic analyses the parameters are considered as random variables, for them assigning a statistical distribution that describes the range of possible values together with their probability of occurrence. Therefore, it is possible to estimate the degree of uncertainty of the individual variables and, since the obtained factor of safety is also considered as a random variable with a probability distribution, the instability of the slope can be calculated. The slope probability of failure, P_f, is related to the reliability index, β (introduced by EC0 as a measure of reliability) by means of the relationship:

$$P_f = \phi\,(-\beta) \tag{7}$$

where ϕ is the cumulative distribution function of the standardised normal distribution.

The probability of failure can be expressed through a performance function g such that a structure is considered to survive when g > 0 (EC0, CEN 2002):

$$P_f = Prob\,(g \leq 0) \tag{8}$$

Thus, the performance function is the factor of safety. If g is a normally distributed function, the reliability index can be calculated as:

$$\beta = \frac{\mu_g - 1}{\sigma_g} \tag{9}$$

where μ_g e σ_g are the mean value and standard deviation of function g respectively.

Different levels of reliability may be adopted. According to EC0 (CEN 2002), a design using partial factors given in EC7 (CEN 2004) is considered generally leading to a minimum threshold value β = 3.8 for a 50 years reference period.

Soil unit weight and shear strength angle have been considered random variables normally distributed, while a lognormal distribution has been assumed for the strength root increment. Fixed coefficients of variation (*COV*) have been assigned to the first two distributions, chosen as the average value of the respective ranges reported in literature (Kulhawy, 1992; Lee et al., 1983; Phoon et al., 1995). On the contrary, the coefficient of variation for the $\Delta\tau$ distribution has been chosen varying along the wide range of values that characterize it in order to study how the uncertainty of data around the mean or expected value affects the reliability of the design practice. *COV* values used in the research are summarized in Table 2. The probabilistic methodology used in this study is the Monte Carlo simulation, generating random values in order to obtain the probability distribution for the factor of safety. Monte Carlo simulations have been performed considering a number of samples equal to *n* = 1000000 in total for each slope stability analysis.

Table 2. Chosen COV values for the current research

Parameter	COV (%)
Soil unit weight	5
Shear strength angle	7
Strength root contribution	20; 40; 60; 80; 100

The aforementioned probabilistic analysis has been performed on the global minimum slip surface identified by the previous deterministic stability analysis, recalculating *n* times the factor of safety with a different set of input variables randomly generated for each analysis. Finally, the probability of failure has been calculated as follows:

$$Pf = \frac{number\ of\ analyses\ with\ FS<1}{total\ number\ of\ analyses} \cdot 100 \quad (10)$$

The reliability index indicates how many standard deviations separate the mean factor of safety (obtained from all the factors of safety calculated for the global minimum slip surface) from the critical one (FS = 1).

Figure 4 shows the reliability index results for varying strength root contribution $\Delta\tau$ and root *COV* values, obtained for a slope having $\alpha = 30°$ and $\phi' = 35°$. The slope configuration with root height $h_r = 2$ m has been analysed since for it the root system has offered an optimal contribution to the slope reinforcement, according to the results previously illustrated.

By analysing the results, it is clear that $COV(\Delta\tau)$ variation highly influences the response of the root-reinforced slope in terms of reliability. The reliability index increases with increasing mean value of strength root contribution when $COV(\Delta\tau)$ values are low (20% and 40%). In particular, β records an increment equal to 32% when the strength root contribution increments from $\Delta\tau = 5$ kPa to $\Delta\tau = 20$ kPa for $COV(\Delta\tau) = 20\%$, and an increment equal to 7% for $COV(\Delta\tau) = 40\%$. For all the other *COV* values, β seems not highly depending on $\Delta\tau$ mean value, effectively cancelling the benefit of the roots to offer a higher strength. Moreover, $\Delta\tau$ mean value being equal, the reliability index decreases with increasing $COV(\Delta\tau)$, as expected; in fact, ranging from $COV(\Delta\tau) = 20\%$ to $COV(\Delta\tau) = 100\%$, the reliability index reaches a decrease equal to 30% for the lower strength root contribution ($\Delta\tau = 5$ kPa) and an even more important decrease (62%) for the higher one ($\Delta\tau = 20$ kPa).

Finally, it should be pointed out that the minimum threshold β value is reached and exceeded only for $COV(\Delta\tau)$ equal to 20% and 40%. This result is remarkable as it involves a very important consideration: although the factor of safety obtained in the deterministic analysis was higher than unity already for $\Delta\tau$ equal to 7 kPa, the reliability cannot be guaranteed for $COV(\Delta\tau)$ higher than 40%. This implies the importance to provide innovative researches that allow defining measurements and models for the evaluation of $\Delta\tau$ that are more reliable.

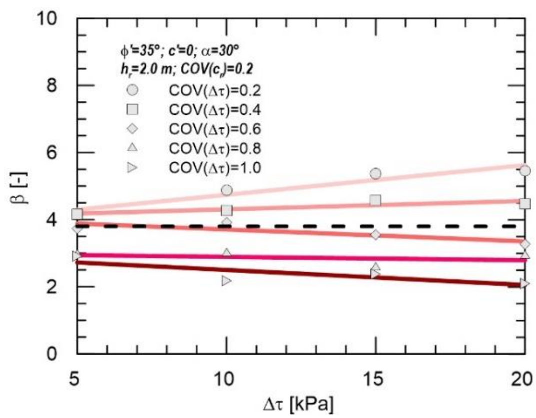


Figure 4. β curves for varying $\Delta\tau$ and $COV(\Delta\tau)$, for $\alpha = 30°$, $\phi' = 35°$ and $h_r = 2$m

4.3 Is the deterministic design reliable?

Figure 5 shows the trend in the reliability index for varying the corresponding factor of safety evaluated according to EC7 (CEN 2004) and for different root heights. The best condition in terms of data uncertainty has been presented for these analyses, using the lowest coefficient of variation ($COV(\Delta\tau) = 20\%$). The points of each single curve represent β-FS pairs obtained for a fixed $\Delta\tau$ mean value (indicated in labels); the dashed and dash-dot lines represent the threshold values of the reliability index ($\beta = 3.8$) and factor of safety ($FS = 1$) respectively, dividing the graph into four quadrants that allow the identification of the area where the slope configuration satisfies both the deterministic and the probabilistic calculation. Analysing the graph it is possible to observe that all the analyses exceeding the threshold $FS = 1$ satisfy even the reliability requirement ($\beta = 3.8$) when $COV(\Delta\tau) = 20\%$. Nevertheless, results change when the other coefficients of variation are considered.

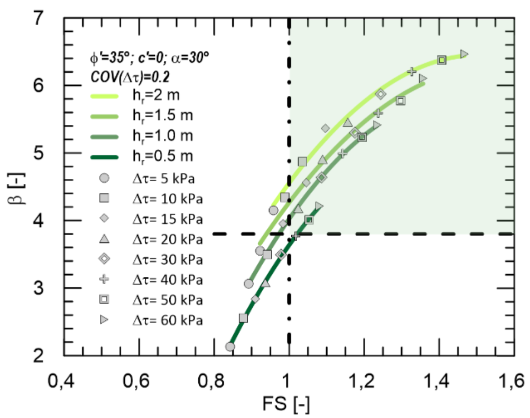


Figure 5. β-FS curves for varying $\Delta\tau$ and h_r, for $\alpha = 30°$, $\phi' = 35°$ and $COV(\Delta\tau) = 20\%$

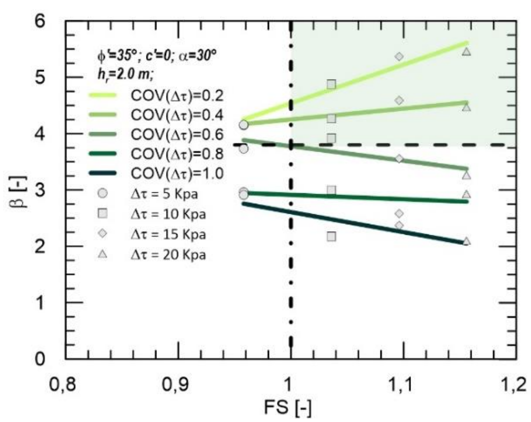


Figure 6. β-FS curves for varying $\Delta\tau$ and $COV(\Delta\tau)$, for $\alpha = 30°$, $\phi' = 35°$ and $h_r = 2m$

For instance, for the same slope configuration ($\alpha = 30°$ and $\phi' = 35°$) and for $h_r = 2$ m, Figure 6 shows the trend in the reliability index for varying the corresponding factor of safety and for all the root coefficients of variation. In this case, results point out that the complete correspondence between both the safety and reliability criteria is missing when $COV(\Delta\tau)$ reaches 60%.

5 CONCLUSIONS

The performed probabilistic analyses have allowed quantifying the influence of the strength root contribution's uncertainty on the deterministic design's reliability of this alternative risk mitigation measures for shallow landslides. With regard to a certain slope configuration, results have shown that a correspondence between both the safety and reliability criteria to be satisfied according to Eurocodes for a proper design cannot be always guaranteed.

As a matter of fact, when the coefficient of variation of the strength root contribution is high, the reliability is not satisfied. This implies the importance to develop innovative researches that allow reducing the uncertainty level which characterise measures, thus refining the models for the evaluation of the root parameters that contribute to increase the soil strength.

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