

Influence of soil-roots interaction on the seismic performance of natural slopes

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ABSTRACT: Vegetation is recognized for its crucial role in enhancing the stability of the upper soil layers on natural slopes. As a result, numerous studies have been conducted in recent decades to gain a deeper understanding of the complex soil-root interaction, as well as the mechanical contribution to the stability of shallow soil layers. Most research has focused on static stability, with relatively few addressing seismic aspects. This paper presents a set of original closed-form solutions based on the infinite slope model that account for the stabilizing effects of roots on both the pseudo-static safety factor and the horizontal component of the slope yield acceleration coefficient. Specifically, by means of a simplified Newmark-type analysis, the effect of vegetation on the seismic performance of the slope is investigated within a performance-based framework, focusing on the reduction of the seismic-induced permanent displacements due to the beneficial effects of soil-root interaction. Several charts are derived that serve as practical design tools for selecting the appropriate increase in slope seismic resistance attributed to soil-root interaction to meet specific design values of the pseudo-static safety factors or earthquake-induced permanent displacements.

Keywords: infinite slope; seismic actions; yield acceleration coefficient; post-seismic permanent displacements

1 INTRODUCTION

It is now widely acknowledged that vegetation, particularly that consisting of herbaceous deep roots- systems, contributes positively to the static stability of the shallowest portion of soil slopes. The fundamental effect that vegetation may exert on the performance of rooted soil is typically considered assuming that roots act as natural fibres, enhancing the soil shear strength mobilisation along potential sliding surfaces. In this framework, the biomechanical properties of roots, including geometric features, profile (e.g. the root area ratio), and mechanical features (e.g. root tensile and pull-out strength), play a central role in determining the overall mechanical behaviour of the composite system. (e.g. Lann et al., 2024; Cecconi et al., 2025). On the other hand, the implementation of soil-vegetation interaction under seismic conditions is less consolidated and remains largely unexplored (e.g. Liang and Knappett, 2017; Karimzadeh et al., 2021; Niu et al. 2026). This topic appears of considerable interest for scientists and national agencies tasked with the management of emergency scenarios and post-emergency actions and countermeasures, related to seismic-induced phenomena over large areas (e.g. Karimzadeh et al., 2021). Pseudo-static and Newmark-type analyses are currently adopted to predict the seismic stability conditions and post-seismic serviceability of rooted soil slopes. In this framework, the paper presents some original solutions derived for the infinite slope scheme. The stabilising effects due to the roots' apparatus are found

to control the pseudo-static safety factor, the slope yield acceleration coefficient and, thus, the magnitude of the expected earthquake-induced permanent displacements.

2 THE INFINITE ROOTED-SLOPE SCHEME

The position of the problem is sketched in Figure 1 where a shallow soil covering (2-3m at maximum) overlaying a stiffer stratum has been considered, being a realistic case for the infinite slope scheme. The roots apparatus is embedded enough to allow accounting for the roots shear strength at the depth H of the sliding surface; both transpiration and suction effects are ignored. For a soil cover with shear strength parameters c' , ϕ' , the pseudo-static safety factor is:

$$F_{E,roots} = \frac{(c' + \tau_{roots})/(\gamma \cdot H)}{\sin \beta \cdot \cos \beta \cdot (1 - k_v) + k_h \cdot \cos^2 \beta} + \frac{\tan \phi' \cdot (1 - r_u) - k_h \cdot \tan \beta - k_v}{\tan \beta \cdot (1 - k_v) + k_h} \quad (1)$$

where γ is the soil unit weight, k_h and k_v are the horizontal and vertical seismic coefficients, β is the slope angle, τ_{roots} is the strength increase due to the mobilization of root resistance and r_u is the pore pressure ratio $r_u = (\gamma_w \cdot H_w) / (\gamma \cdot H)$. If $k_h = k_v = 0$, Equation (1) provides the static factor of safety of the rooted soil slope:

$$F_{s,roots} = \frac{(c' + \tau_{roots})/(\gamma \cdot H)}{\sin \beta \cdot \cos \beta} + (1 - r_u) \cdot \frac{\tan \phi'}{\tan \beta} \quad (2)$$

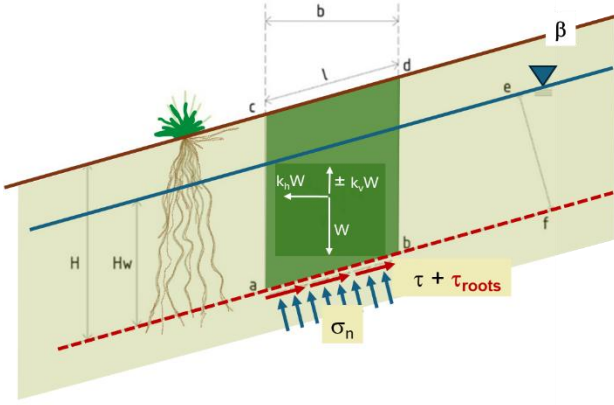


Figure 1. Infinite rooted-slope scheme upon seismic actions

As known, soil-root interaction mechanism is characterized by a progressive mobilization with slips of the root resistance. This feature cannot be not captured in the framework of a pseudo-static analysis; thus, in Equation (1), τ_{roots} will be assumed as a constant and equal to the peak strength increase corresponding to the full mobilization of root resistance; the influence of this approximation is discussed later in the paper.

In the framework of a Newmark-type displacement analyses, the horizontal component $k_{h,c}$ of the slope yield acceleration coefficient can be detected by imposing a unit value of the pseudo-static coefficient; accordingly, the value $(k_{h,c})_{\text{roots}}$ of the yield acceleration coefficient for the rooted-soil slope can be derived through Equation (1) that, for $F_{E,\text{roots}}=1$, leads to:

$$(k_{h,c})_{\text{roots}} = \frac{(c' + \tau_{\text{roots}})/(\gamma \cdot H)}{1 + \tan \phi' \cdot \tan \beta} + \frac{\tan \phi' \cdot (1 - r_u) - \tan \beta}{1 + \tan \phi' \cdot \tan \beta} - k_v \cdot \tan(\phi' - \beta) \quad (3)$$

Equation (3) shows that $(k_{h,c})_{\text{roots}}$ is time-dependant since depends on the current value of k_v and on τ_{roots} that mobilizes progressively as earthquake-induced slips develop. According to Liang et al. (2015), due to the small roots' diameters, root-soil interaction mobilizes very rapidly and the assumption of an instantaneous achievement of the peak root resistance can be considered as a reasonable practical approximation. Accordingly, as for $F_{E,\text{roots}}$ (Equation 1) a constat peak value τ_{roots} will be considered herein assuming the full mobilization of root resistance.

A rigid-plastic model with an associated flow rule is also involved in the derivation of previous equations. According to Liang & Knappett (2017) and Liang et al. (2020), these two assumptions imply shortcomings that can be overcome by using a proper value ϕ'_{mob} of the mobilized friction angle that depends on the soil dilation angle and on the ratio between the shear stress acting along the sliding surface under seismic loading condition and the corresponding effective normal stress.

For roots systems, the value of τ_{roots} at a given depth can be expressed by introducing the *Root Area Ratio*

profile (*RAR*) that, according to the literature, generally decreases with depth, although, even for the same species, the variability at the same location and depth can be very high (e.g. Bischetti et al., 2009). As a consequence, the contribution τ_{roots} can be considered in the evaluation of $F_{E,\text{roots}}$ (Equation 1) and $(k_{h,c})_{\text{roots}}$ (Equation 3) if the tensile strength and total length of the root apparatus are larger enough to ensure that: *i*) tensile failure does not occur as a consequence of the deformation process associated to the earthquake-induced ground motion; *ii*) the soil-roots interaction takes place without reaching the pullout conditions.

Finally, if $\tau_{\text{roots}} = 0$ is assumed, Equations (1), (2) and (3) provides the pseudo-static (F_E) and the static (F_S) factor of safety and the yield acceleration coefficient ($k_{h,c}$) of the unrooted infinite soil slope scheme, i.e. without accounting for the stabilizing effect due to the roots shear strength increment.

3 INFLUENCE OF ROOTS ON THE PREDICTED SEISMIC PERFORMANCE

The stabilizing effect due to the full activation of the root shear strength increase can be quantified in terms of increments in the pseudo-static factor of safety and yield acceleration coefficient in comparison to the unrooted condition:

$$\Delta F_E = F_{E,\text{roots}} - F_E = \frac{\tau_{\text{roots}}/(\gamma \cdot H)}{\sin \beta \cdot \cos \beta \cdot (1 - k_v) + k_h \cdot \cos^2 \beta} \quad (4)$$

$$\Delta k_{h,c} = (k_{h,c})_{\text{roots}} - k_{h,c} = \frac{\tau_{\text{roots}}}{\gamma \cdot H} \frac{1}{1 + \tan \phi' \cdot \tan \beta} \quad (5)$$

According to Equation (4) the increment ΔF_E is not affected by the soil friction angle but depends on the slope angle β , the seismic coefficients k_h and k_v and on the normalized value of the roots shear strength increase $\tau_{\text{roots}}/(\gamma H)$.

For $\tau_{\text{roots}}/(\gamma H)$ in the range 0-0.5, that covers most of the practical cases concerned with the shallow rooted soil coverings considered herein ($H=2-3\text{m}$), Figure 2a shows the values of ΔF_E computed for $\beta = 15^\circ$ and 30° and horizontal seismic actions ($k_v = 0$) described by $k_h = 0.1-0.3$. It is clear that, for a given value of $\tau_{\text{roots}}/(\gamma H)$, the larger are β and k_h , the lower is the increment in the pseudo-static safety factor. As an example, in the case $\beta = 15^\circ$ with $k_h = 0.2$ it is $\Delta F_E \approx 0.46$ and 0.92 for $\tau_{\text{roots}}/(\gamma H)$ equal to 0.2 and 0.4 respectively, meaning roots shear strength increase τ_{roots} of about 6 to 20 kPa, that sounds reasonable for the case at hand ($H=2-3\text{m}$, $\gamma=16-18 \text{ kN/m}^3$).

Conversely, in the case $\beta = 30^\circ$ (together with $k_h = 0.2$ and $\tau_{\text{roots}}/(\gamma H) = 0.2-0.4$) it is $\Delta F_E \approx 0.34-0.68$.

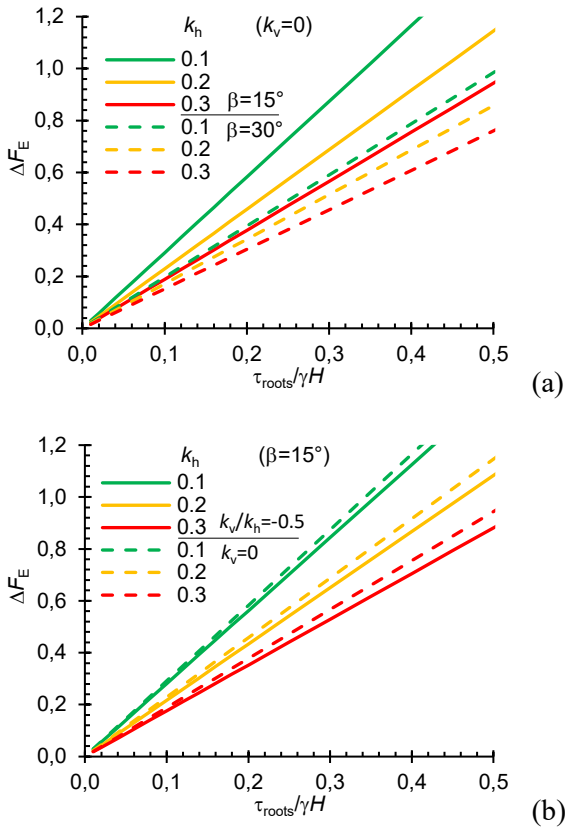


Figure 2. Increment of the pseudo-static factor of safety versus the normalized roots shear strength increase

On the other hand, as it is shown in Figure 2b, where the case $\beta = 15^\circ$ is addressed assuming also $k_v/k_h = -0.5$ (according to Equation (4), negative k_v is the worst condition), these results are not significantly affected by the value of the vertical seismic coefficient.

Concerning the increment in the yield acceleration coefficient, Equation (5) points out that, again, $\Delta k_{h,c}$ depends on the slope angle and is linearly related to the normalized roots shear strength increase $\tau_{\text{roots}}/(\gamma H)$ but it is also affected by the soil friction angle ϕ' .

The value ϕ' is to be considered as the mobilized value ϕ'_{mob} selected according to the findings by Liang and Knappett (2017). Specifically, denoting with ϕ'_{pk} and ϕ'_{cs} the peak value of the soil friction angle and the value at critical state, respectively, ϕ'_{mob} is always in the range $\phi'_{\text{cs}} \div \phi'_{\text{pk}}$ but, since related to the acting shear and normal stresses, it is actually time dependent and should be computed within a displacement analysis carried out for a given acceleration time-history.

For the same values of $\tau_{\text{roots}}/(\gamma H)$ already considered in Figure 2, Figure 3 provides $\Delta k_{h,c}$ for values of the slope (β) and friction (ϕ') angles that cover most of the cases of practical interest. It is worth nothing that, some of the combinations of slope and friction angles considered in Figure 3 define a rooted soil slopes for which an effective cohesion c' is required to ensure the static stability conditions (the condition $c' > 0$ usually characterizes unsaturated shallow rooted soil coverings).

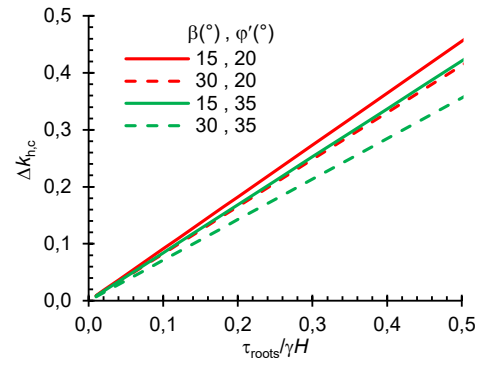


Figure 3. Increment of the yield acceleration coefficient versus the normalized roots shear strength increase

From Figure 3, it is clear that, regardless ϕ' , the lower increments in the yield acceleration coefficient concern with steeper slopes (i.e. larger slope angles); as an example, in the case $\tau_{\text{roots}}/(\gamma H) = 0.4$ with $\phi' = 20^\circ$ it is $\Delta k_{h,c} = 0.36$ and 0.33 in the cases $\beta = 15^\circ$ and 30° , respectively; similarly, if $\phi' = 35^\circ$ is considered with the same slope angles it is $\Delta k_{h,c} = 0.34$ and 0.28 .

As for τ_{roots} , also the value of the mobilized friction angle to be used in the evaluation of the yield acceleration coefficient (Equation 3) and of its increment (Equation 5) is time dependent and should be evaluated within a displacement analysis.

However, a preliminary evaluation of the reduction in the magnitude of the earthquake-induced permanent displacements due to the presence of the roots shear strength increase, can be obtained by assuming several values of ϕ'_{mob} within its proper range of variation ($\phi'_{\text{mob}} = \phi'_{\text{cs}} - \phi'_{\text{pk}}$). Also, simplified semi-empirical predictive equations, derived in the framework of conventional Newmark-type analyses using different ground motion databases, can be used (e.g. Jibson 2007; Biondi et al. 2011; Cho and Rathje 2022). These predictive equations generally provide the magnitude of the expected permanent displacement as a function of a series of ground motion parameters (describing the characteristic of the input motion) and of the slope yield acceleration coefficient assumed as an index of seismic slope resistance. Herein, a predictive equation proposed by one of the Authors is adopted even if the obtained results are general validity from a qualitative point of view.

Starting from a large set of conventional Newmark-type analysis, carried out with reference to the scheme of unrooted infinite soil slope subjected to only horizontal seismic actions, Biondi et al. (2011) proposed the following relationship between the expected permanent displacement d and the acceleration ratio $k_{h,c}/k_{h,\text{max}}$ i.e. the ratio between the horizontal yield acceleration (unrooted case) and the peak horizontal acceleration of the acceleration time-history selected as input motion:

$$\log d = B - A \cdot \frac{k_{h,c}}{k_{h,\text{max}}} \quad (6)$$

In Equation (6) d is in cm and the dimensional fit constants A and B depends on the soil class and peak ground

acceleration expected at the site of interest and fall in the ranges $A \approx 3.51\text{--}4.07$ cm and $B \approx 2.28\text{--}2.60$ cm.

By applying Equation (6) to the cases of unrooted and rooted soil slopes (yield acceleration coefficients equal to $k_{h,c}$ and $(k_{h,c})_{\text{roots}}$ respectively) it is easy to derive the following equation giving the ratio between the permanent displacements d_r and d_{ur} relative to the rooted and the un-rooted cases:

$$\log \frac{d_r}{d_{ur}} = -A \cdot \frac{\Delta k_{h,c}}{k_{h,\max}} \quad (7)$$

By using the values of $\Delta k_{h,c}$ already presented in Figure 3 and assuming $A = 3.51$ cm and 3.78 cm (corresponding to expected peak ground acceleration equal to $0.35g$ and $0.15g$, respectively, and soil class *C*, *D* or *E* according to Eurocode 8), Figure 4 shows the corresponding values of the ratio d_r/d_{ur} .

Regardless the peak horizontal seismic coefficient $k_{h,\max}$ and the values of the slope and friction angles selected for the analyses, depending on the normalized roots shear strength increase $\tau_{\text{roots}}/(\gamma H)$, the reduction in the expected permanent displacements can be extremely relevant, highlighting the relevant influence of the stabilizing effect due to the full activation of the root shear strength increase. The larger reductions (i.e. lower values of the ratio d_r/d_{ur}) have been computed for the larger $k_{h,\max}$ and β , that imply the lower values of the yield acceleration coefficient $k_{h,c}$ (un-rooted case) and, thus, the larger permanent displacements for the un-rooted case. This finding points out the relevance of the stabilising effects of the roots' apparatus on the seismic performance of shallow soil coverings. This result appears of general validity since not significantly affected by: *i*) the assumptions introduced herein concerning the mobilization of root resistance; *ii*) the displacement predictive model considered in the numerical analysis.

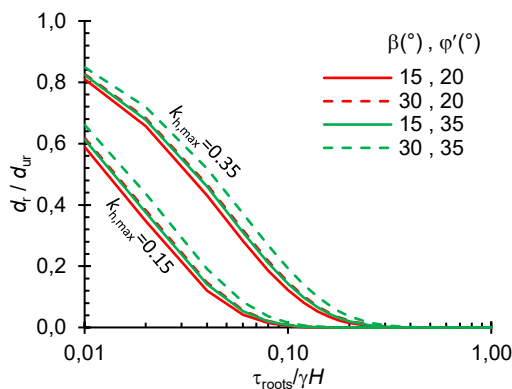


Figure 4. Reduction in the expected slope permanent displacement versus roots shear strength increase computed according to the predictive model by Biondi et al. (2011)

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