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Assessing the influence of root reinforcement on slope stability by finite elements

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Abstract

This paper aims to investigate the effect of root reinforcement on slope stability using finite element methods. It is well recognised that plant roots can improve the shear strength of soils by their high tensile strength and closely spaced root matrix system. The increase in soil shear strength due to root reinforcement is considered as an increase in apparent soil cohesion, called root cohesion, c_r. In this paper, a freely available (http://www.inside.mines.edu/~vgriffit/slope64) finite element code called slope64 described by Griffiths and Lane (Géotechnique 49(3):387–403, 1999) is used to model the effect of root reinforcement on slope stability. The root cohesion is added directly to the soil cohesion for the soil elements that are reinforced by plant roots. The results from the finite element analyses demonstrate that the factor of safety of a slope increases when the effect of root reinforcement is taken into consideration. A series of stability charts are developed which can be used for assessing the influence of root reinforcement on slope stability.

Keywords: Root reinforcement, Root cohesion, Slope stability, Finite element methods

Background

Plant roots can reinforce the soil due to their tensile strength and adhesional properties. The inclusion of plant roots with high tensile strength increases the confining stress in the soil mass by its closely spaced root matrix system. The soil mass is bound together by the plant roots and the soil shear strength is increased by providing additional apparent cohesion to the soils [2–5]. However, plant roots have a negligible effect on the friction angle of soils due to their random orientation [6]. Therefore, the enhanced soil shear strength due to root reinforcement can be considered equivalent to the increase in apparent soil cohesion, c_r. As a result, the Mohr–Coulomb equation for soil shear strength can be modified as follows [2]:

$$s = c' + c_r + (\sigma_n - u)\tan\phi' \tag{1}$$

where s is the shear strength of the soil; c' is the effective soil cohesion; c_r is the apparent soil cohesion; σ_n is the normal stress; u is the pore water pressure; and ϕ' is the effective friction angle.

Over the years, many studies have been conducted to quantify the contribution of root reinforcement to soil shear strength. These studies include in situ direct shear tests on soil blocks with plant roots (e.g. [3, 7–12], and laboratory direct shear tests of soils with roots (e.g. [4, 13, 14] or soils reinforced by fibres that simulate roots (e.g. [15–18]. These studies together give evidence on the increase in soil shear strength due to root reinforcement. It was generally found that the increase in soil shear strength due to root reinforcement is directly proportional to the root density.

The increase in shear strength of soil due to root reinforcement is equivalent to an additional apparent cohesion, which is also known as root cohesion, c_r, and this value can be estimated based on three different methods: (1) the perpendicular root reinforcement model developed by Wu et al. [5] with the available root density and tensile strength information; (2) field or laboratory direct shear tests; and (3) back analysis on failed slopes. In the literature, many researchers have estimated the value of root cohesion for different vegetation species growing in different environments, and typical values of these are summarised in Table 1. It is noted that the typical values for c_r vary from 1.0 to 94.3 kPa depending on the vegetation species and environments. However, the

Table 1 Typical values for root cohesion, c_r

Investigators	Vegetation	c_r (kPa)
Endo and Tsuruta [3][a]	Alder (Japan)	2.0–12.0
Swanston [28][b]	Hemlock, spruce (Alaska, USA)	3.4–4.4
O'Loughlin [29][b]	Conifers (British Columbia, Canada)	1.0–3.0
Burroughs and Thomas [30][c]	Conifers (Oregon, USA)	3.0–17.5
Wu et al. [5][c]	Conifers (Alaska, USA)	5.9
Gray and Megahan [31][b]	Ponderosa pine, Douglas-fir (Idaho, USA)	2.8–6.2
Waldron and Dakessian [32][a]	52-month-old yellow pine (Laboratory)	~5.0
Waldron et al. [14][a]	54-month-old yellow pine (Laboratory)	3.7–6.4
Sidle and Swanston [33][b]	Blueberry, devils's club (Alaska, USA)	2.0
Riestenberg and Sovonick-Dunford [34][c]	Sugar maple forest (Ohio, USA)	6.2–7.0
Wu [35][c]	Sphagnum moss (Alaska, USA)	3.5–7.0
	Hemlock, sitka spruce (Alaska, USA)	5.6–12.6
Abe and Iwamoto [7][a]	Japanese cedar (Japan)	1.0–5.0
Buchanan and Savigny [36][b]	Grasses, sedges, shrubs, sword fern (USA)	1.6–2.1
	Red alder, hemlock, Douglas-fir, cedar	2.6–3.0
Abernethy and Rutherfurd [8][c]	River red gum (Victoria, Australia)	10.0
	Swamp paperbark	19.0
Schmidt et al. [20][c]	Natural forest—conifers (Oregon, USA)	25.6–94.3
	Industrial forest—hardwood	6.8–23.2
	<11-year-old clearcuts	1.5–6.7
Simon and Collision [37][c]	Sycamore (Mississippi, USA)	7.0
	River birch	8.0
	Sweetgum	4.0
	Gamma grass	6.0
	Black willow	2.0
	Switch grass	18.0

[a] Based on direct shear tests

[b] Based on back analysis

[c] Based on perpendicular root reinforcement model with measurements of root density and tensile strength

majority of the values fall within the range of 1.0–20.0 kPa. With the estimated value of root cohesion, c_r, the increase in factor of safety (FOS) of a slope due to root reinforcement can be calculated accordingly using conventional slope stability analysis methods, i.e. limit equilibrium methods, which has been conducted by many researchers (e.g. [5, 19–22]. These studies involved modifying the original FOS equations of limit equilibrium methods to include the additional root cohesion.

This paper aims to assess the effect of root reinforcement on slope stability using finite element methods and develop a series of stability charts for vegetated slopes. When compared to the conventional limit equilibrium methods the finite element method has the advantage of not requiring an a priori assumption of the shape and location the critical slip surface. This is particularly useful when considering the effect of root reinforcement because the critical slip surface is usually complex and unknown when vegetation is present.

Finite element model

The finite element analysis is based on an elasto-plastic, stress–strain law with a Mohr–Coulomb failure criterion. It uses eight-noded quadrilateral elements and reduced integration in both the stiffness and stress distribution parts of the algorithm. The plastic stress distribution is accomplished by using a visco-plastic algorithm. The theoretical basis of the finite element method and the first ever published source code for elasto-plastic slope stability analysis was described by Smith and Griffiths [23, 24]. In brief, the analyses involve the application of gravity loading and the monitoring of stresses at all Gauss points. If the stresses at a point exceed the strength of the material at that point, as defined by the Mohr–Coulomb failure criterion, the program attempts to redistribute excess stress to neighbouring elements that still have reserve strength. This iterative process continues until the Mohr–Coulomb failure criterion and global equilibrium are satisfied at all points within the mesh under strict tolerances. The FOS of a soil slope is defined as the factor by which the original shear strength parameters must be divided in order to bring the slope to the point of failure [1]. The factor of safety is therefore defined as:

$$c'_f = c' / \mathrm{FOS} \tag{2}$$

$$\phi'_f = \tan^{-1}\left(\phi' / \mathrm{FOS}\right). \tag{3}$$

The effect of root reinforcement can be taken into account in the finite element slope stability analysis by adding the root cohesion, c_r, to the effective soil cohesion, c', of the soil to give a total cohesion, c_T, as given by:

$$c_T = c' + c_r. \tag{4}$$

In the finite element model, the soil elements that are affected by vegetation (known as the 'root zone') are assigned the total cohesion, c_T, while, for other soil elements within the slope geometry, the effective soil cohesion, c', is used. It is noted that the total cohesion, c_T, are used in the strength reduction process as given in Eq. (2). The typical finite

element model that consists of a root zone is shown in Fig. 1. The grey shaded areas indicate the root zone and the extent of this root zone from the ground surface is defined by the parameter called the 'depth of root zone', h_r. This is the effective distance beyond which plant roots are assumed to cause little or no effect on the soil shear strength.

The depth of root systems varies significantly with vegetation species and their growing environments [25]. About 60–80 % of grass roots are found in the top 50 mm of soil [2]. For trees and shrubs, the most widely reported range was 1–3 m [26]. However, deeper root systems had been reported, for example, William and Pidgeon [27] noted gum tree rooting to 27.5 m. In North America, the depth of rooting is usually constrained by bedrock at relatively shallow depths (less than 2 m) in many slopes [20].

Numerical studies and computed results

Two sets of analyses were performed. Firstly, the influence of spatial distribution of vegetation is examined, followed by the effect of root cohesion. These are discussed, in turn, below.

Effect of spatial distribution of vegetation on slope stability

Numerical analyses, using the finite element model, were carried out to investigate the effect of root reinforcement on slope stability. A 2H:1V homogenous slope ($\beta = 26.6°$) with a height, H, of 10 m was considered. The assumed soil properties were: $\gamma = 20$ kN/m^3; $c' = 1$ kPa; and $\phi' = 25°$. It should be noted that vegetation could grow on any region of a natural slope. Therefore, in the first part of the numerical analyses, the effect of the spatial distribution of vegetation on the stability of a slope was investigated. Vegetation was considered growing on different locations of a slope, as shown in Fig. 2. In this study, the root cohesion, c_r, and the depth of root zone, h_r, were held constant at 10 kPa and 2 m, respectively. The factor of safety (FOS) for each slope case shown in Fig. 2 was computed and summarised in Table 2.

It is noted that, without including the effect of root reinforcement in the slope stability analysis (i.e. Case 1), the computed FOS for the slope is 1.05, which indicates the slope is marginally stable. When vegetation grows on the entire slope (i.e. Case 8), the FOS increases from 1.05 to 1.25 (i.e. 19 % increase), which has the most significant increase in FOS among all other cases. This is followed by the case with vegetation growing on

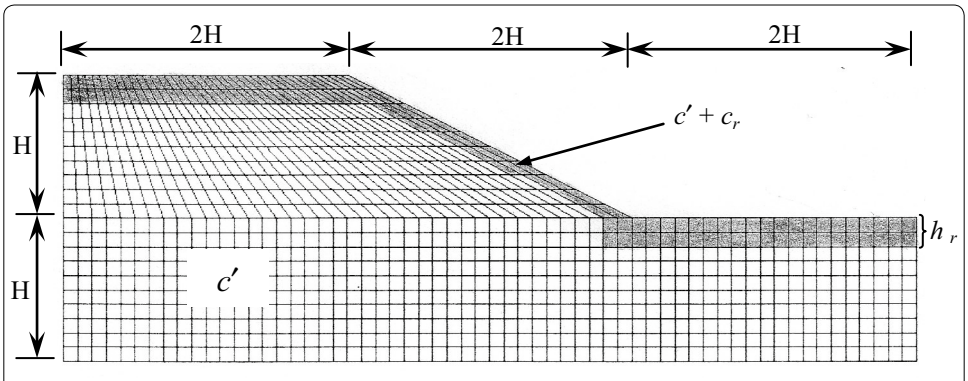

Fig. 1 Typical finite element mesh for incorporating effect of root reinforcement

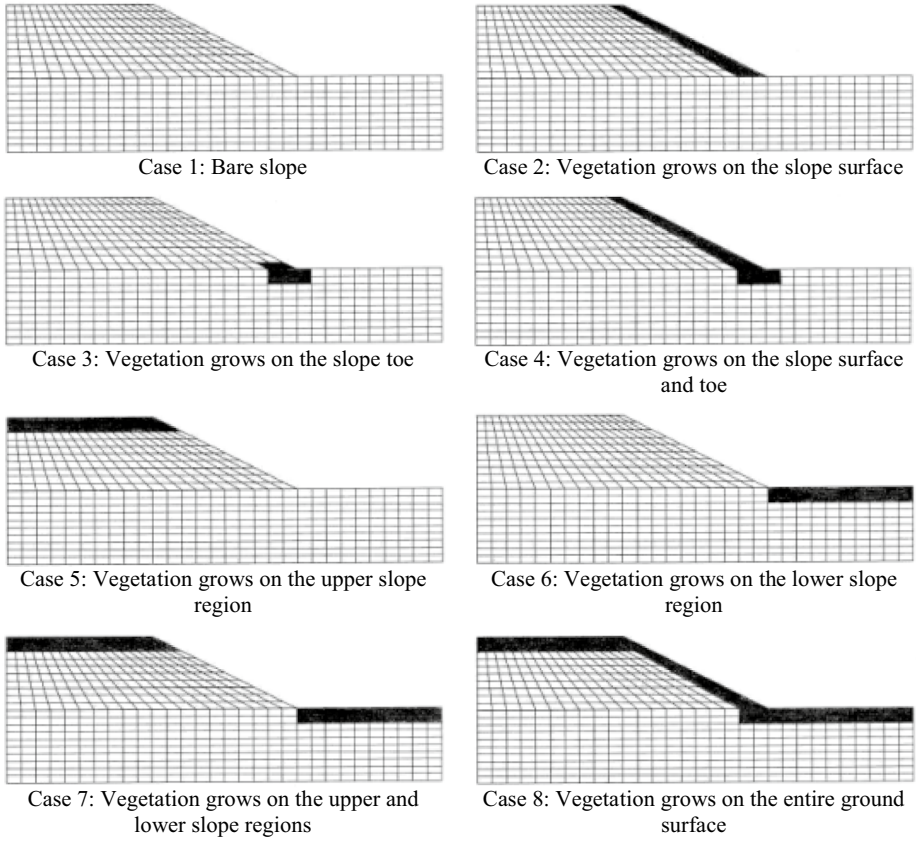

Fig. 2 Vegetated slope with different locations of root zone

Table 2 Computed FOS for the slope with different locations of root zone

Case	FOS	Increase (%)
1	1.05	–
2	1.08	3.0
3	1.05	0.0
4	1.20	15.0
5	1.08	3.0
6	1.05	0.0
7	1.08	3.0
8	1.25	19.0

the slope surface and toe (i.e. Case 4) and, in this case, the FOS increased to 1.2 (i.e. 15 % increase). However, when vegetation was grown only on the slope surface (i.e. Case 2) or on the upper slope region (i.e. Case 5), the increase in FOS was only 3 %. Furthermore, when vegetation was grown only on the slope toe (i.e. Case 3) or on the lower slope region (i.e. Case 6), no improvement in FOS was observed. These results suggest that vegetation should be grown on the entire ground surface of a slope or at least on the slope surface and toe, so that the beneficial effect of the root reinforcement on slope stability can be obtained.

Effect of root cohesion on slope stability

In the second part of the analyses, vegetation was assumed to grow on the entire ground surface (i.e. Case 8) and the value of c_r was varied between 1 and 20 kPa, while a h_r of 1 and 2 m was considered. The results of these analyses are shown in Fig. 3. It can be seen that the FOS of a vegetated slope (i.e. $c_r > 0$) is higher than that of a bare slope (i.e. $c_r = 0$). The increase in the FOS is dependent on the values of c_r and h_r. Generally, the FOS increases with the values of c_r and h_r. For example, for an intermediate value of c_r (i.e. $c_r = 10$ kPa), the FOS increased from 1.05 to 1.16 for the case with $h_r = 1$ m, and the FOS increased from 1.05 to 1.25 for the case with $h_r = 2$ m, or a 10 and 19 % increment, respectively. For a relatively high value of c_r (i.e. $c_r = 20$ kPa), the increments were 19 and 34 %, respectively. It is noted that the percentage increase in the FOS is not directly proportional to the increment in the values of c_r. It is expected that the FOS will approach a maximum limiting value as the value of c_r keeps increasing. However, this maximum limiting value for the FOS was not investigated here because the extremely large values of c_r are unlikely to be encountered in real slopes. Despite this, the results show that root reinforcement provides a significant improvement on the stability of a slope. The results also indicate that a marginally stable slope could become stable when the effect of root reinforcement is taken into consideration. In other words, adopting the alternative perspective, an originally stable vegetated slope could become marginally stable or unstable after vegetation is removed.

Figure 4 shows the effects of varying the values of c_r on the FOS of the slope with different values of effective soil cohesion, c', i.e. 1, 5, 10 and 20 kPa, while the other parameters are held constant at: $\gamma = 20$ kN/m^3; $\phi' = 25°$; and $h_r = 1$ m. The computed FOS for the slopes with c' of 1, 5, 10 and 20 kPa, without considering the effect of root reinforcement (i.e. $c_r = 0$), are 1.05, 1.33, 1.59 and 2.05, respectively. It is noted that the FOS increases as c_r increases for all the cases of c' considered. The maximum percentage increments in the FOS of the slopes with c' of 1, 5, 10 and 20 kPa, which were obtained when $c_r = 20$ kPa, are 19.4, 10.6, 7.8 and 5.3 %, respectively.

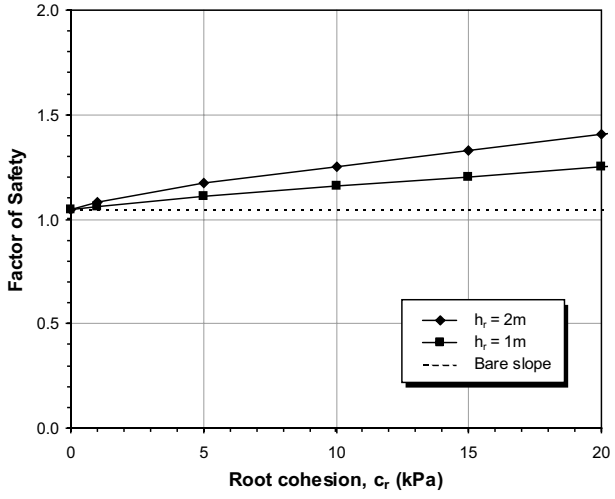

Fig. 3 FOS versus root cohesion for different depths of root zone ($c' = 1$ kPa; $\phi' = 25°$; 2H:1V slope)

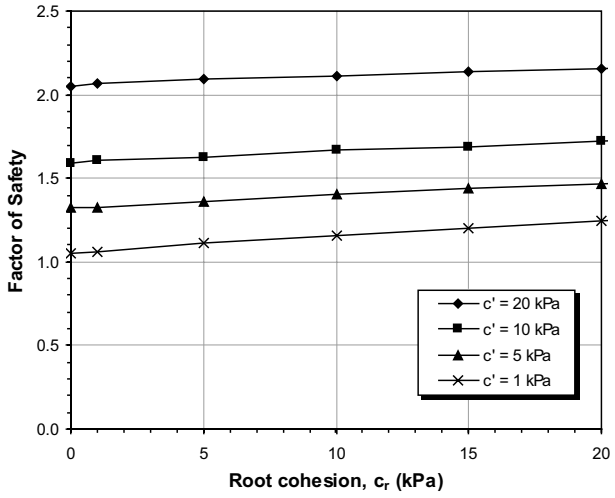

Fig. 4 FOS versus root cohesion for different values of effective cohesion of soil ($\phi' = 25°$; $h_r = 1$ m; 2H:1V slope)

Clearly, the slope with the lowest value of c' (i.e. lowest FOS) showed the highest percentage increment in the FOS when $c_r = 20$ kPa. In fact, the same phenomenon is observed for the cases with other values of c_r. This finding suggests that root reinforcement provides greater improvement to the stability of a slope with a lower FOS than a slope with a higher FOS.

Figure 5 shows the plots of the FOS versus root cohesion, c_r, for the slopes with different values of friction angle, ϕ', i.e. 5°, 15°, 25° and 35°, while the other parameters are held constant at: $\gamma = 20$ kN/m^3; $c' = 1$ kPa; and $h_r = 1$ m. The FOS for the slopes with ϕ' of 5°, 15°, 25° and 35°, without considering the effect of root reinforcement (i.e. $c_r = 0$), are 0.27, 0.64, 1.05 and 1.53, respectively. It is noted that the slopes that with ϕ' of 5° and 15° are considered to be unstable or 'failed'.

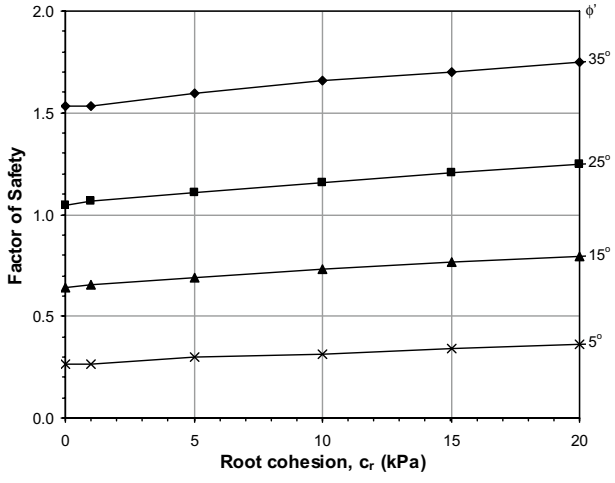

Fig. 5 FOS versus root cohesion for different values of effective friction angle of soil ($c' = 1$ kPa; $h_r = 1$ m; 2H:1V slope)

It can be seen from Fig. 5. that the FOS increases as c_r increases for all cases of ϕ' considered. The maximum percentage increments in FOS of the slopes with ϕ' of 5°, 15°, 25° and 35° are 35.0, 24.3, 19.4 and 14.3 %, respectively. This observation is similar to that previously found in Fig. 4 where the slope with a lower FOS obtains a greater in FOS than the slope with a higher FOS. The results in Fig. 5 once again confirm that root reinforcement provides greater improvement to the stability of a slope with a lower FOS than a slope with a higher FOS.

Development of stability charts for vegetated slopes

In order to construct slope stability charts that can be used for assessing the effect of root reinforcement on slope stability, extensive parametric studies were carried out. The input parameters were systematically varied according to the values shown in Table 3. A total of 768 different combinations of input parameters were obtained based on the values shown in Table 3. The slope angles, β, of 18.4°, 26.6°, 45.0° and 63.4° correspond to slopes of 3H:1V, 2H:1V, 1H:1V and 0.5H:1V, respectively. It is noted that the effective soil cohesion, c', is expressed as a dimensionless stability coefficient, c'/γH. For example, when $\gamma = 20$ kN/m^3 and $H = 10$ m, values of $c'/\gamma H$ of 0.1, 0.05, 0.025 and 0.005 correspond to a c' of 20, 10, 5 and 1 kPa, respectively. The constructed stability charts are presented in Figs. 6, 7, 8 and 9.

It can be observed from Figs. 6, 7, 8 and 9 that, for all slope angles, FOS increases linearly as root cohesion increases. It is also noted that the increase in FOS is more significant for the steeper slopes and those with a lower value of FOS. This observation suggests that vegetation is a useful method of slope stabilisation, especially for steep slopes with a low value of FOS.

Discussion

The finite element analysis results show that root reinforcement can provide a significant improvement on the stability of a slope. As expected, the factor of safety (FOS) of a slope increases as the root reinforcement properties (i.e. apparent root cohesion and depth of root zone) increase. However, the improvement on FOS is not only governed the apparent root cohesion and depth of root zone but also dependent on the underlying soil properties of the slope and slope geometry. Slopes with low effective soil cohesion tend to gain more improvement on FOS than slopes with high effective soil cohesion. Similarly, steeper slopes tend to gain more improvement on FOS than slopes with shallower slopes. This is because the failure mechanism for a slope with low effective soil cohesion is likely to be shallow seated failure and failure surface is usually located closer

Table 3 Input variables and values for parametric studies undertaken

Input variables	Values
Slope angle, β (°)	18.4, 26.6, 45.0, 63.4
Friction angle, ϕ' (°)	5, 15, 25, 35
Stability coefficient, c'/γH	0.1, 0.05, 0.025, 0.005
Root cohesion, c_r (kPa)	0, 1, 5, 10, 15, 20
Depth of root zone, h_r (m)	1, 2

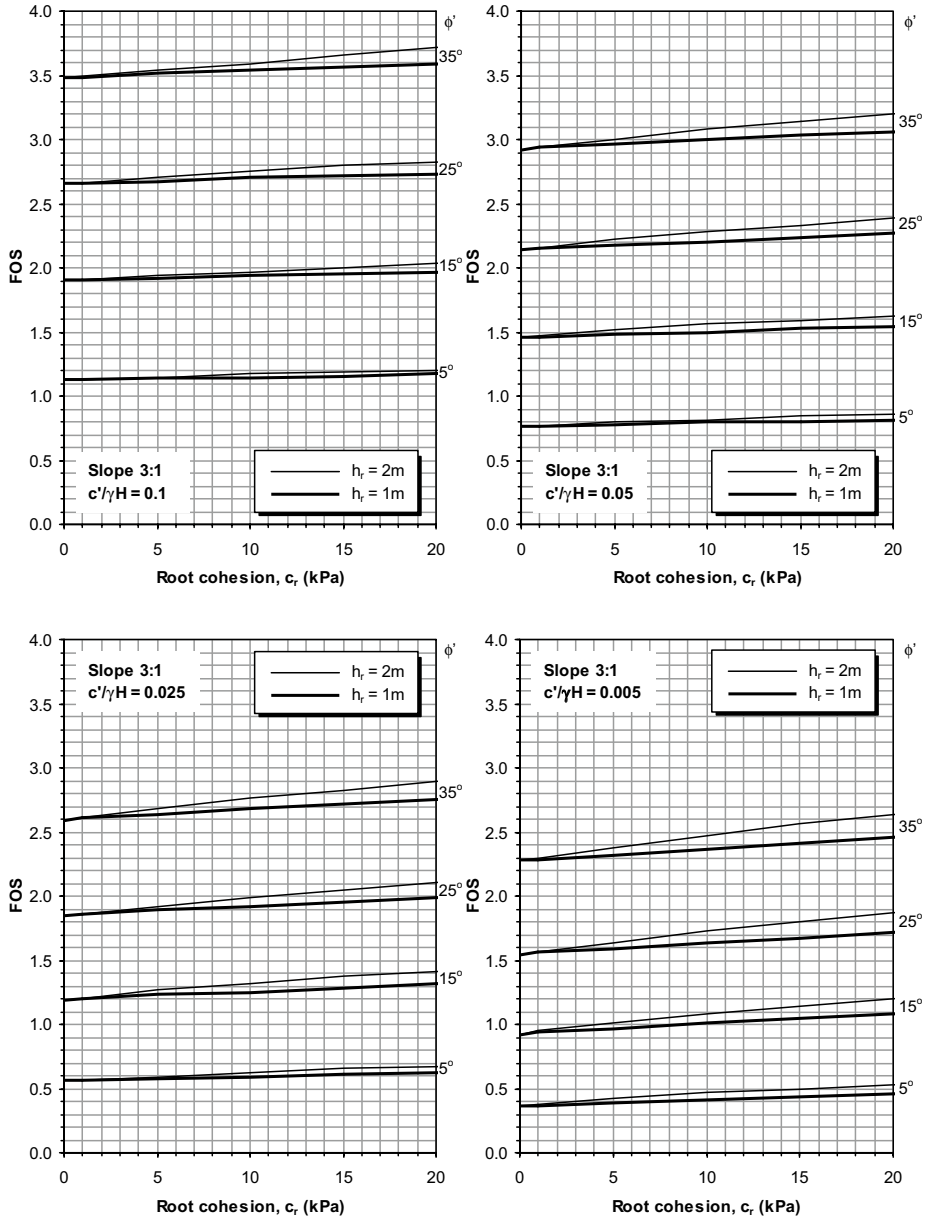

Fig. 6 Stability charts for 3H:1V (β = 18.4°) vegetated slope

to the sloping ground surface where most of vegetation roots are confined into. Hence, the presence of vegetation roots has effectively reinforced the weaker zone of the slope by proving additional apparent cohesion to the soils and 'pushed' the failure surface deeper into the slope which ultimately increase the FOS. Similarly, steeper slopes which are more prone to shallow seated failure gain more improvement on FOS due to root reinforcement that confined to the sloping ground surface.

Summary and conclusions

In this paper, the effect of root reinforcement on slope stability has been modelled using the finite element method. The root cohesion, c_r, has been considered as additional

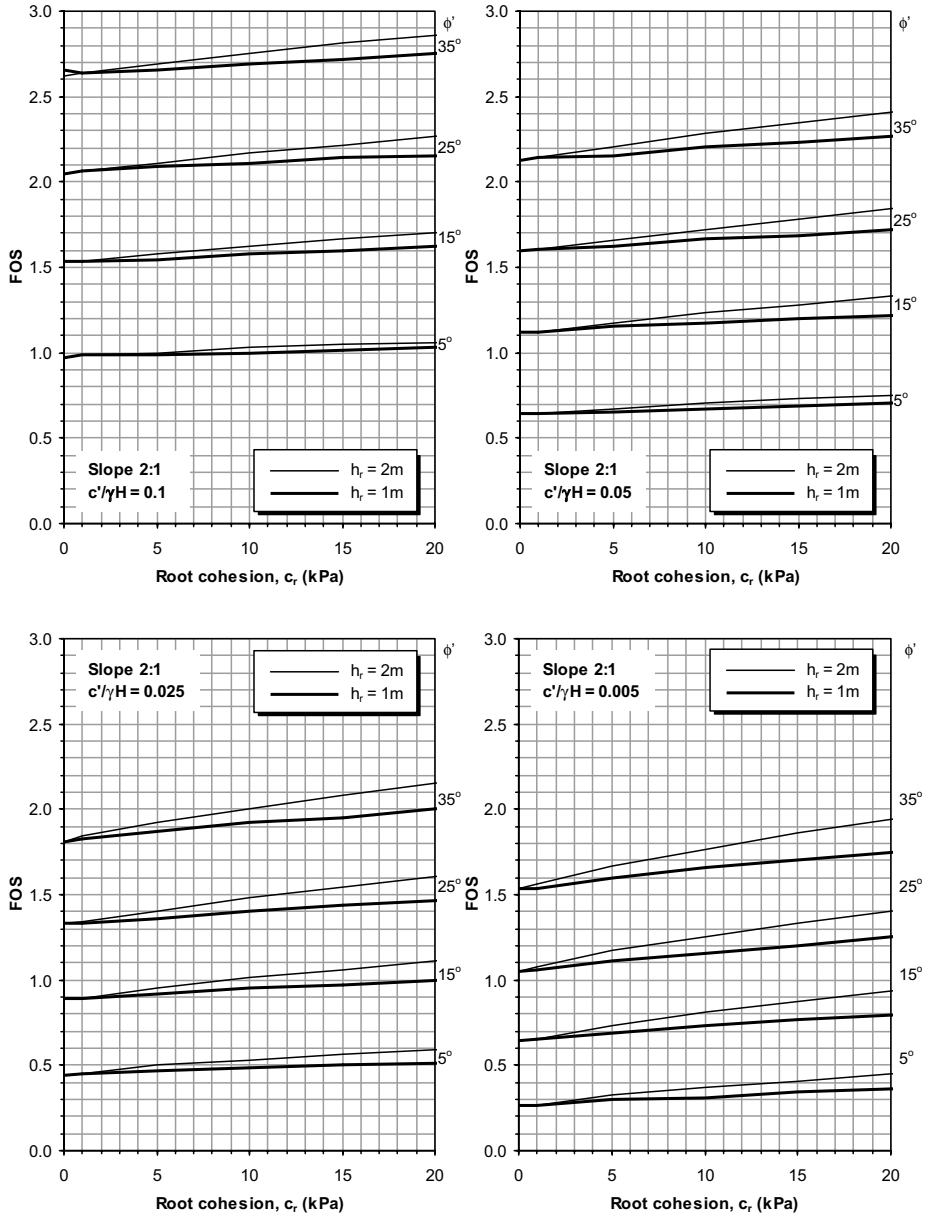

Fig. 7 Stability charts for 2H:1V (β = 26.6°) vegetated slope

apparent cohesion, which is added to the soil cohesion. The soil elements within the defined slope geometry that are affected by vegetation are known as the 'root zone', and the extent of this root zone is defined by the 'depth of root zone', h_r. The results from the numerical analyses conducted using the finite element model show that the factor of safety (FOS) of a slope increases when the effect of root reinforcement is taken into consideration. In general, the FOS increases linearly with c_r and h_r. It has been found that

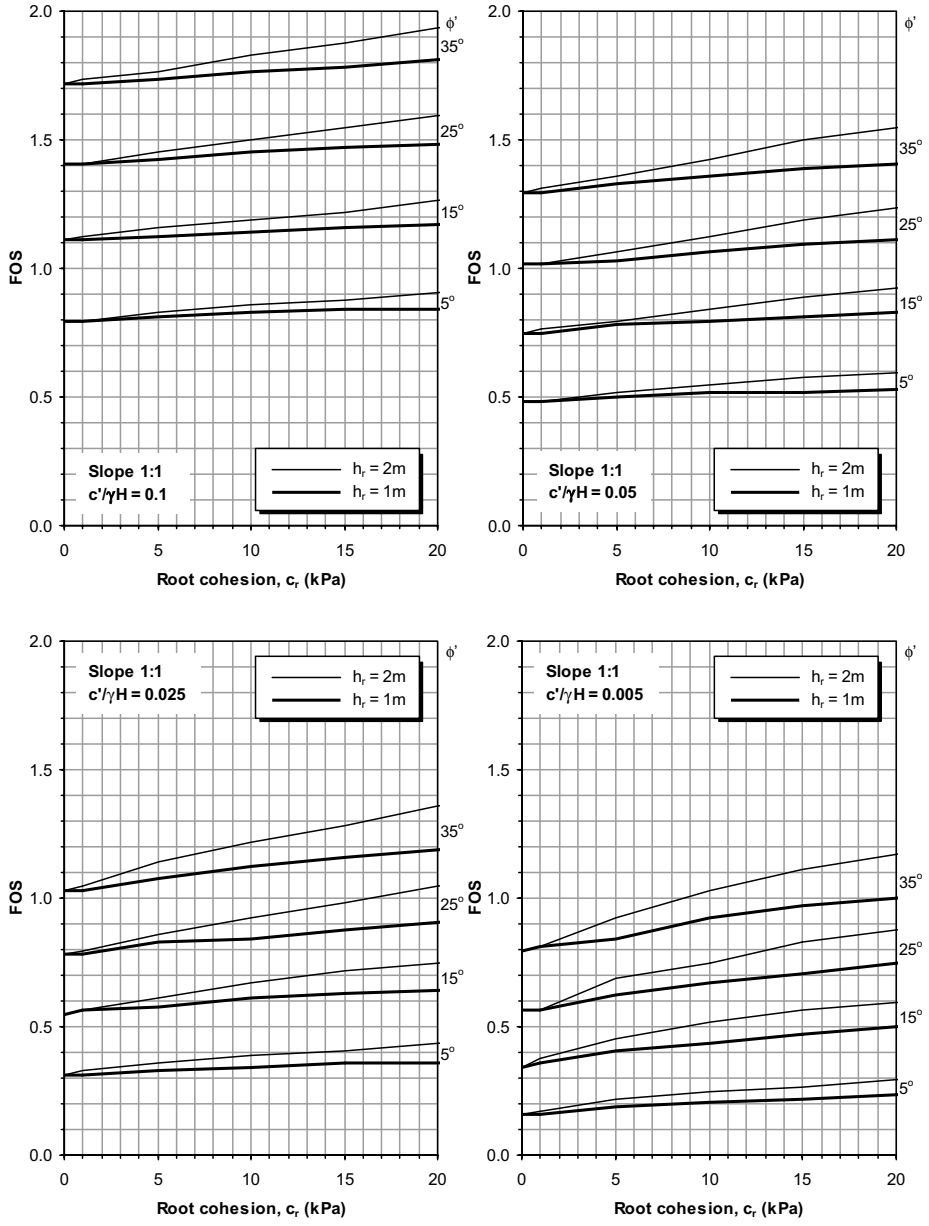

Fig. 8 Stability charts for 1H:1V ($\beta = 45°$) vegetated slope

the increase in FOS is more significant for the slopes with a lower value of FOS than for those with a higher FOS.

Extensive parametric studies using the finite element method have been conducted to generate a series of stability charts that can be used for determining the FOS of a vegetated slope. Five variables were varied systematically to determine the corresponding value of FOS for each case. The variables considered are the slope angle, β, friction angle,

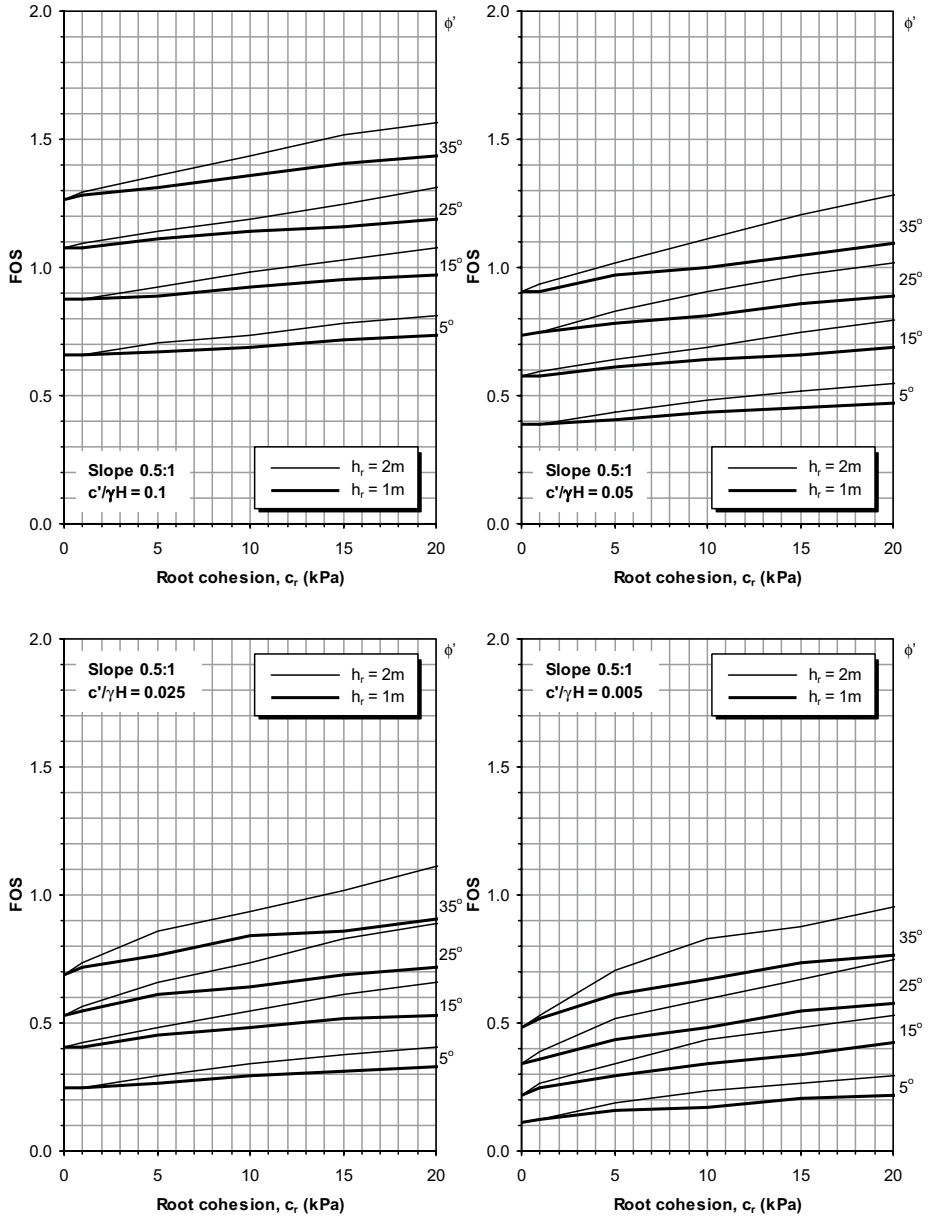

Fig. 9 Stability charts for 0.5H:1V ($\beta = 63.4°$) vegetated slope

ϕ', stability coefficient, $c'/\gamma H$, root cohesion, c_r, and depth of root zone, h_r. The developed stability charts can be used as a quick tool for assessing the effect of root reinforcement on slope stability.

Authors' contributions

YHC carried out the numerical analysis and drafted the manuscript. MBJ, WSK and DVG checked and reviewed the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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