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RESEARCH ARTICLE

Evaluation of Slope Stabilization by Vegetation Reinforcement: Modelling Aspects

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ABSTRACT

In geotechnical engineering, slope stability is one of the main issues. In order to strengthen the safety factor of slopes against failure, this study focuses on the numerical evaluation of planting (vegetation) reinforcement as an environmentally beneficial strategy. For this purpose, the Mohr-Coulomb failure model incorporates the apparent root cohesion—a physical contact between the vegetation root and the soil structure. Thus, utilizing parametric investigation, both the numerical and limit equilibrium methods are used to assess the impacts of root cohesion (Cr) and root depth (Zr) corresponding to different types of plants and trees on the safety of various slopes. The considered Cr and Zr values are (0,5,10,15,20, and 25 kPa) and (0,0.5,1.0,1.5 and 2.0 m), respectively. These values are looked at in a variety of instances involving slopes with slope angles (β°) of 18.4°,26.6°,33.7°,39.8°,45°, and 55°. Additionally, the consequences of slope sections that might become vegetated are simulated in various circumstances, and the outcomes are contrasted with a root-free strategy. The findings show that increasing root cohesiveness and depth improves the slope's stability. Even in scenarios with steep slopes (i.e. β>45°)., this rise is noteworthy. According to the results, scenarios where vegetation is integrated onto the slope's surface have a higher safety factor than crest and toe covered zones. Furthermore, there is no evidence of any impact from the vegetation cover in the toe region.

Keywords: Slope stability; vegetation; soil reinforcement; numerical modelling; parametric study.

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1-INTRODUCTION

Many slopes that were stable for several years can abruptly fail due to changes in the slope geometry, climatic and stress conditions (such as weathering, excessive unplanned excavation, rise in groundwater table, rainfall and surcharge loads) and plate tectonics (earthquake). Therefore, it is important for geotechnical engineers to understand how to properly evaluate this problem and to follow a suitable and cost-effective measure to achieve slope stabilization and increase its factor of safety against failure. The common types of slope stabilization methods are: (i) installation of drainage system, (ii) retaining walls, (iii) Rock stabilization method, (iv) soil nailing and (v) planting or vegetation on slope (Arbanas and Arbanas, 2014).

Planting of slopes (vegetation or root reinforcement) is considered as an effective, sustainable and environmentally friendly way to stabilize a slope and to decrease the probability of slope failure. The roots of the soil from direct impact of raindrops, hence, slow down surface flow and allow precipitation to infiltrate rather than flow down. In General, the influence of vegetation includes both hydrological effects and mechanical effects. Within the concepts of hydrological effects, vegetation plays an important role in changing the soil moisture regime through evapotranspiration process, which lead to an increase in soil suction (negative pore water pressure), thus, increase the soil shear strength (Simon and collision, 2002 Greenwood et al., 2004). The mechanical effects are about the increase of strength of soil driven by physical interaction between roots of the plant and soil structure (root reinforcement).

The vegetation's root reinforcement effect can be considered in conventional slope stability calculations by adding the term apparent root cohesion (Cr) that can be incorporated in the Mohr-Coulomb envelope for soil as $\tau = (C + Cr) + \sigma' \tan\emptyset$. Where τ is shear strength of soil, σ′ is normal effective stress, C is cohesion and ϕ is angle of internal friction. The Cr values are calculated in previous research from various types of fields and using laboratory tests such as direct shear and triaxial tests. Chok (2008) reported the available Cr values in the literature that are measured from different experimental studies on soil systems that are covered by specific type of vegetation. Table (1) summarizes some of these reported Cr values for various types of vegetation. Depth of root zone (Zr) is the other key vegetation-dependent parameter in the mechanical interaction of the soil-root system. Stokes et al. (2009) listed the following values of Zr for rooting depth of different types of plants (Table 2).

Table 1: Cr-values for different types of vegetation covers (after Chok, 2008).

Type of Plant	*Cr* (kPa)	Researchers
Grasses, sedge, shrubs (USA)	1.6-2.1	Buchanan and Savigny (1990) [a]
lodgepole pine (California, USA)	3-21	Ziemer (1981) [b]
Japanese Cedar	1-5	Abe and Iwamoto (1986) [b]
conifers (Oregon, USA)	3-17.5	Burroughs and Thomas (1977) [c]
River red gum (Victoria, Australia)	10	Abernethy and Rutherfurd (2001) [c]
Wamp paperbark (Victoria, Australia)	19	
Switch grass (Mississippi, USA)	18	Simon and collision (2002) [c]
Gamma grass (Mississippi, USA)	6	

a Based on back analysis , b Based on direct shear test, c Based on perpendicular root reinforcement model with measurements of root density and tensile strength

Table 2: Zr-values of different types of plants (Stokes et al., 2009).

Plant	Rooting depth (m)
Annuals herbs and forbs	< 0.5
Perennial herbs and forbs	0.75
Shrubs and trees on deep soils	2.2
Shrubs and trees growing on shallow soils over bedrock	7.9

Wu (1984) used an analytical method to evaluate the effects of both i) changes in the soil moisture regime and (ii) soil strength by the roots driven by vegetation on the FoS of the slopes. Chok et al. (2004) examined the effects of Cr and Zr on the slope stability using finite element method. Results show that vegetation plays an important role in the stabilization of the slopes; and the FoS increased by increasing Cr and Zr values. In their study the apparent root cohesion (Cr) was varied over the range of (0 to 20 kPa); and the depth of 1m, 2m, 3m are evaluated for Zr. The strong role of lateral root reinforcement on the increase of the slope stability is also highlighted by Schwarza et al. (2010). Recently, a detailed review of the effects of vegetation on slope stability using numerical and limit equilibrium methods has been reported by Wu et al. (2015). In their research, the mechanical and hydrological effects for the complex interaction between soil, plant, water and atmosphere have been investigated. In addition, Wang et al. (2020) studied the combined mechanical effects (additional cohesion effects and anchorage effects) of vegetation on a slope with coarse-grained soil in a certain mountainous region of Gansu Province, China. The numerical results of the problem indicated that the factor of safety (FoS) of the slope was increased by the presence of trees. The enhancing effects of FoS were most significant when the trees were planted along the entire slope.

The focus of this study is on evaluation of soil reinforcement by roots (vegetation) as an approach to improve the stability of slopes. The numerical and limit equilibrium analyses are performed using SLOPE/W and SIGMA/W packages of GeoStudio software. It is well-known that different types of vegetation affect slope stability in different ways. Therefore, in the first phase of study, the effects of both the root cohesion (Cr) and the depth of the root zone (Zr), to represent various type of vegetation, are examined in this study using parametric study and for different inclination angles (β°) of slopes. The results of these modelling approaches (numerical and limit equilibrium analyses) subjected to all these parameters are reported in terms of factor of safety of slope and they are compared with the case with no-vegetation cover. In the second phase of study, the effects of location of the vegetation cover on slope is numerically investigated in different scenarios.

2 -APPLICATIONS

The problem is about medium stiffness clayey slope with 1V/2H inclination (β=26.6°) that is underlying a stiff rock layer. The distance from the crest to the left boundary is 25m and from the toe of the slope to the right boundary is 20 m (Figure 1). It is assumed that the model is not subjected to the external surcharge loading. The thickness of the soil layer is 20m and 10m on the left and right sides of the model respectively. The rock layer is not included in the geometry; instead, an appropriate boundary condition is applied at the bottom of the soil layer. The shear strength parameters of the model are 5.0 kPa, 25° for cohesion and angle of internal friction respectively. The bulk unit weight of the soil is 19 kN/m3. The groundwater level is not encountered in the model. For numerical analysis, first the geometry of the model and the corresponding finite element mesh and its initial conditions of stress are developed in SIGMA/W and then its slope stability analysis is performed using SLOPE/W feature of GeoStudio software.

The slope is defined in SIGMA/W with the assumed elastic soil medium of 25000 kPa Modulus of Elasticity and 0.3 Poisson’s ratio. The finite element mesh is generated with 1231 nodes and 2298 elements. Figure (2) shows a final geometry of the model and the various boundary conditions applied on finite element mesh. For the left and right sides of the model the Fixed-X type of the boundary condition is used. However, the assigned boundary condition for the bottom boundary of the model is the Fixed X/Y type to represent the impervious rock layer. The upper boundary of the model is a free surface.

Finally, the SLOPE/W package is added to the model for analyzing the factor of safety of the studied slope considering the SIGMA/W stresses as the parent for the analysis type. The Mohr- Coulomb is used as the material model in a stability analysis with the shear strength parameters of 5.0 kPa and 25° for cohesion and angle of internal friction respectively. For slope stability analysis the portions of the ground surface where the slip surface can enter and exit have to be specified. Entry range is assigned on the ground surface starting 5 meters from the left boundary up to the crest point of the slope. And the start point of the Exit range is the toe point of the slope up to the range of 5 meter away from the right-hand side boundary of the model on the ground surface.

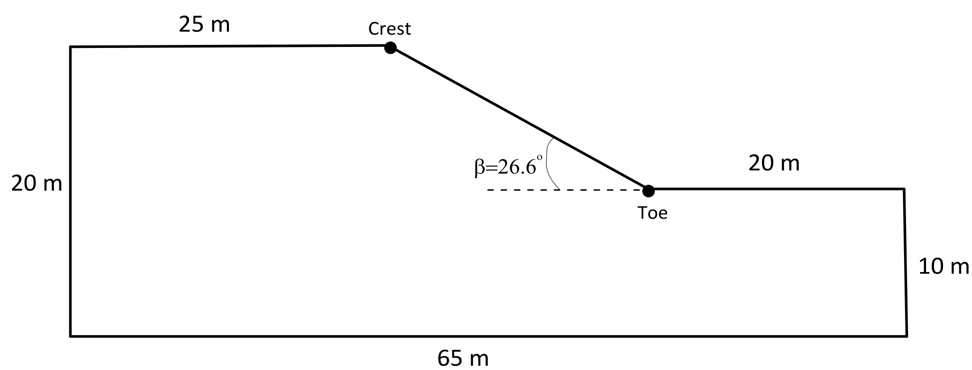


Figure 1: Geometry of the case study example.

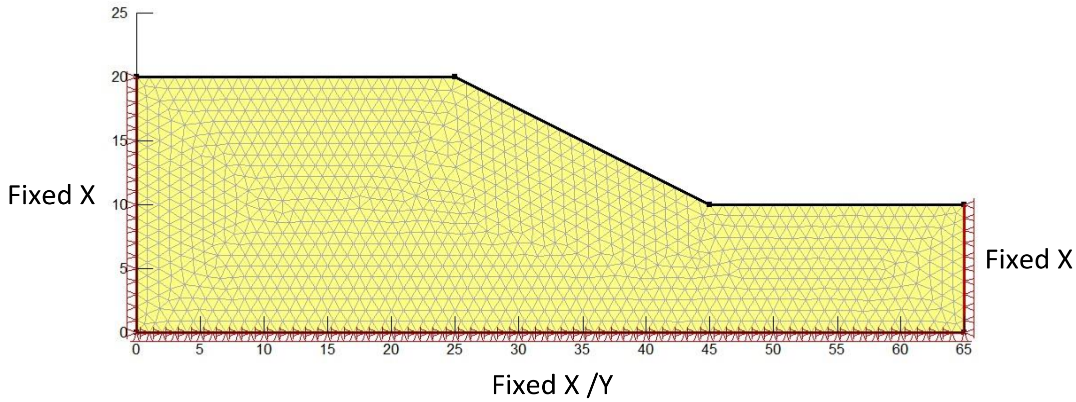


Figure 2: Finite element mesh and the applied boundary conditions of the model.

3 -PARAMETRIC STUDY: SCENARIOS OF VEGETATION REINFORCEMENT

In the first phase of the study, the slope of the studied example is modified to include the root zone influence. For this purpose, the surface of the model is divided into two distinct regions. The depth of the top layer (Zr) is considered to be equivalent to the depth of the root zone for a specific type of vegetation (plants) (Figure 3). The slope stability analysis is performed for different values of this depth parameter (Zr=0,0.5,1.0,1.5 and 2m). By changing the soil cohesion of this upper layer, the effects of the apparent soil cohesion (Cr) induced by the root zone (Cr=0, 5,10,15,20 and 25 kPa) are also added to the cohesion of soil. These effects are simulated for different slope angles (β°=18.4, 26.6, 33.7,39.8, 45 and 55°) and using both numerical and limit equilibrium (LE) methods and the results are compared. Figure (4) illustrates the geometrical view of all these slopes. In order to define the desired slope geometry, the location of the toe point and the height of the slope (10 m) are kept fixed and only the location of the crest point is extended to the left or right sides. All other input parameters, Young's modulus of elasticity, Poisson's ratio, unit weight and internal angle of friction of the soil are kept unchanged. Moreover, the effects of the surcharge load on the slope are ignored throughout this research.

In the second phase of the study the effects of the location of the vegetation cover on the factor of safety of the slopes are numerically evaluated. The slope of β=26.6° is purposely used in this evaluation considering the Zr=2m and Cr=5 kPa. Figure (5) shows different vegetation root arrangements utilized in the numerical modelling. The influence of vegetation covers for entire model surface are included in Case1. In case 2 only the vegetation on crest and slope are incorporated in the simulation. Within the scenario 3 the planting on the slope and the toe are focused. In case 4 it is assumed that only the slope surface is planted; and finally, the case 5 is analyzed with no vegetation on its slope surface (only toe and crest are covered).

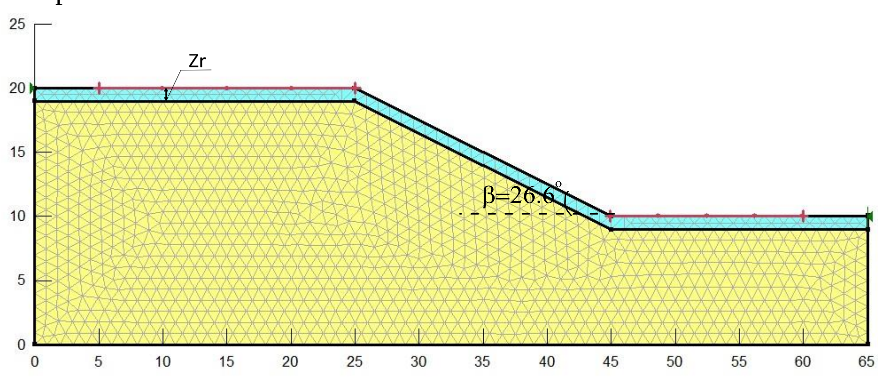


Figure 3: Definition of the vegetation layer of depth (Zr) in the modelling process of the slope β=26.6º.

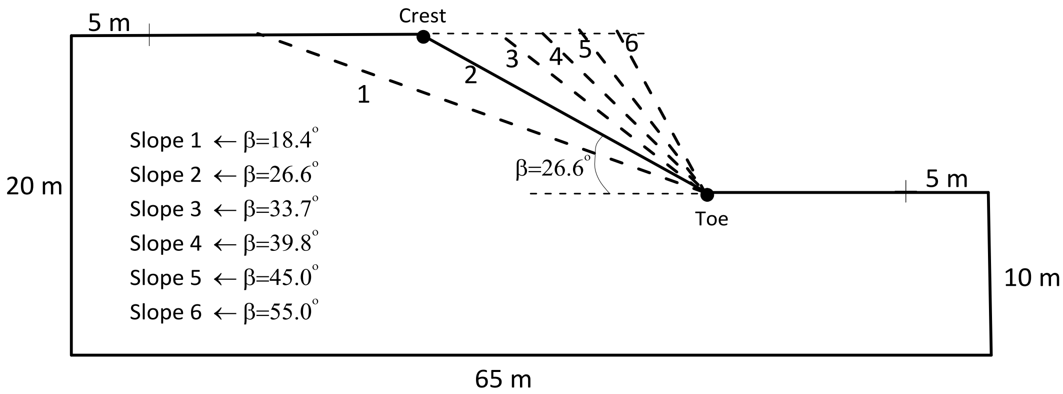


Figure 4: Different slopes considered in the numerical and LE simulations.

4 -RESULTS AND DISCUSSION

Tables (3) shows the summary of the results of the factor of safety (FoS) analysis of slopes 26.6° and 55° and for all studied Cr and Zr values using both numerical and LE techniques respectively. Ordinary method of slices, Bishop's simplified, Janbu's simplified, Morgenstern-Price methods are used for LE analysis. These values represent the FoS of the most critical slip surfaces (with the smallest FoS), which are automatically identified among all the possible slip surfaces. Generally, the numerical analysis resulted in the larger values of safety factor than the LE. Among the LE approaches used, the results of Bishop and Morgenstern-Price methods are comparable to numerical outputs and this is the dominant trend in all the results throughout this study. The ordinary method of slices is the first and simplest LE method that commonly used for slope stability and thus it is purposely used in the following separate sections to discuss the influence of each of Zr, Cr and β° parameters on the safety of the slopes.

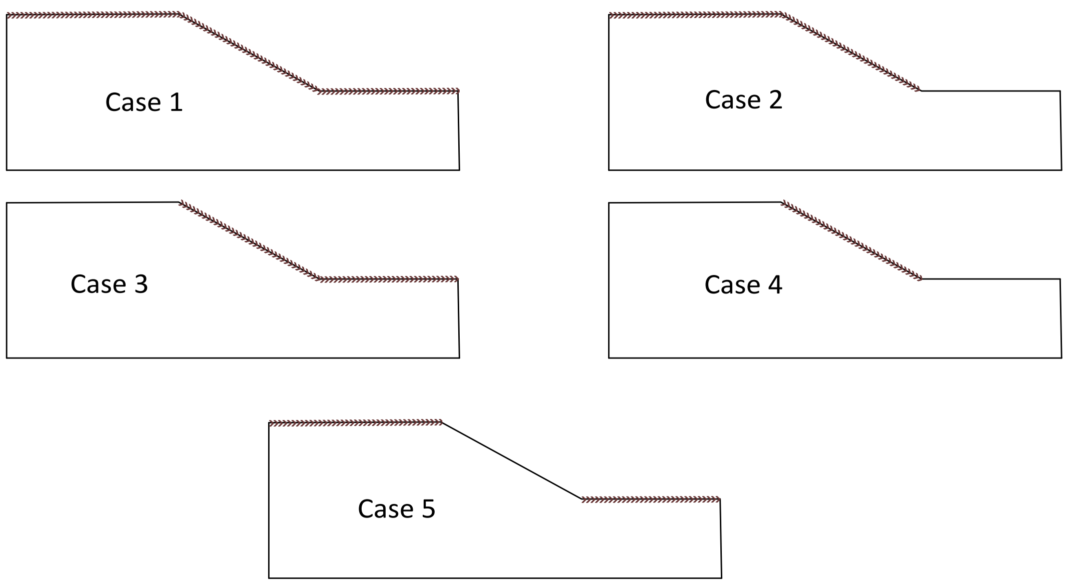


Figure 5: Different scenarios of the vegetation cover for the numerical modelling.

4-1 Effects of Depth of the Root Zone (zr):

The factor of safety of the slopes are analyzed for different values of the Zr (0.5, 1, 1.5, 2 m). The findings are then compared with the case with no vegetation cover zone (Zr=0 m). Figure (6) depicts the results of FoS analyses for numerical and ordinary (ordinary method of slices)-LE methods estimated for the slope β=26.6º and for the cases with Cr=5 kPa and Cr=25 kPa.

For the case with the slope angle of *β*=26.6º, the estimated critical FoS values with no vegetation are almost 1.457 from the numerical and 1.322 from the ordinary- LE calculations (see Table 3). Compared with the case with no root reinforcement (*Zr*=0 m), the results manifest that increasing *Zr* from 0 to 2.0 m for the case of *Cr*=5 kPa results in a 6.5 % increase in FoS value. This increase ratio is 18.3% for the case with *Cr*=25 kPa. The corresponding estimated rate of increase by increasing the depth of the root zone is 21.4% obtained via ordinary-LE method in the case with *Cr*=25 kPa. In order to make the comparison easier, for the slope of *β*=26.6º for example, and for all *Cr* values (0 to 25 kPa) and *Zr* values (0 to 2.0 m) the results of both Numerical and ordinary-LE techniques are illustrated using Figure (7). This figure clearly indicates that the deeper root zone possesses the larger values of the critical FoS and thus improves the stability of the slope.

4-2 Effects of Root Cohesion (Cr)

The model is executed for different values of root cohesion (*Cr*): 5,10,15,20 and 25kPa. These values are chosen based on the values suggested in the literature for different types of the vegetation (typically between 0 and 25 Pa). Figure (8) presents the increasing trends of the FoS with increasing of *Cr* values for the slopes 26.6° and 55.0°. For the slope *β*=26.6˚ with the root depth *Zr* = 0.5m, these changes of *Cr* values resulted in numerical values of FoS of 1.477,1.498, 1.520, 1.538 and 1.563 respectively (table 3). Consequently, the associated rate of improvement of the critical safety factors are 1.4%, 2.8 %, 4.3%, 5.6% and 7.3% respectively with respect to the case with no vegetation (FoS=1.457). For the case with *Zr*=2.0 m, these rates of improvement are 6.5%, 10.5%, 13.0%, 15.7% and 18.3% for the *Cr* values equal to 5,10,15,20 and 25kPa respectively.

Table 3: Summary of the critical values of FoS obtained for slopes β=26.6° and 55°.

β°	*Cr* (kPa) / *Zr* (m)		0	5	10	15	20	25
26.6°	0.5	N	1.457	1.477	1.498	1.520	1.538	1.563
		M	1.403	1.424	1.443	1.463	1.483	1.503
		B	1.406	1.426	1.446	1.466	1.486	1.505
		O	1.322	1.343	1.363	1.384	1.404	1.425
		J	1.322	1.330	1.353	1.375	1.397	1.425
	1	N	1.456	1.500	1.539	1.578	1.597	1.616
		M	1.404	1.445	1.487	1.528	1.570	1.611
		B	1.406	1.448	1.489	1.530	1.572	1.613
		O	1.322	1.365	1.407	1.442	1.465	1.489
		J	1.308	1.354	1.399	1.445	1.491	1.537
	1.5	N	1.457	1.518	1.581	1.611	1.644	1.673
		M	1.403	1.470	1.536	1.603	1.645	1.673
		B	1.406	1.473	1.538	1.604	1.647	1.675
		O	1.322	1.390	1.445	1.481	1.518	1.555
		J	1.308	1.379	1.431	1.474	1.518	1.588
	2	N	1.457	1.550	1.610	1.647	1.686	1.723
		M	1.404	1.496	1.588	1.647	1.685	1.722
		B	1.407	1.498	1.590	1.648	1.686	1.724
		O	1.322	1.416	1.473	1.523	1.568	1.605
		J	1.309	1.403	1.460	1.518	1.569	1.607
55.0°	0.5	N	0.979	0.996	1.013	1.029	1.037	1.047
		M	0.724	0.744	0.761	0.938	0.947	0.957
		B	0.725	0.745	0.764	0.797	0.818	0.839
		O	0.705	0.731	0.756	0.782	0.807	0.833
		J	0.710	0.742	0.744	0.826	0.862	0.898

	1	N	0.983	1.018	1.035	1.066	1.082	1.104
		M	0.723	0.766	0.968	0.986	1.005	1.024
		B	0.725	0.767	0.809	0.851	0.892	0.933
		O	0.705	0.759	0.812	0.865	0.919	0.972
		J	0.710	0.775	0.843	0.912	0.984	1.016
	1.5	N	0.983	1.036	1.067	1.098	1.129	1.161
		M	0.724	0.955	0.985	1.013	1.042	1.071
		B	0.726	0.794	0.862	0.930	0.997	1.064
		O	0.706	0.791	0.875	0.960	1.033	1.063
		J	0.711	0.813	0.919	1.004	1.035	1.066
	2	N	0.993	1.032	1.087	1.134	1.178	1.218
		M	0.724	0.968	1.003	1.043	1.082	1.120
		B	0.725	0.825	0.924	1.023	1..082	1.123
		O	0.706	0.826	0.947	1.039	1.075	1.120
		J	0.711	0.853	0.994	1.033	1.077	1.210

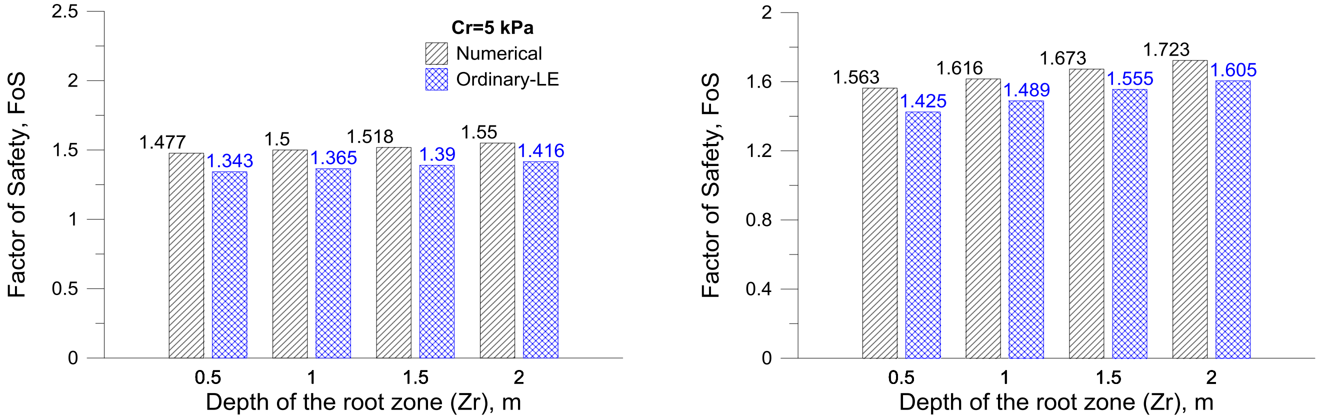


Figure 6: Variation of the FoS with depth Zr for the cases with a) Cr=5 kPa and b) Cr=25 kPa (β=26.6º).

(a)

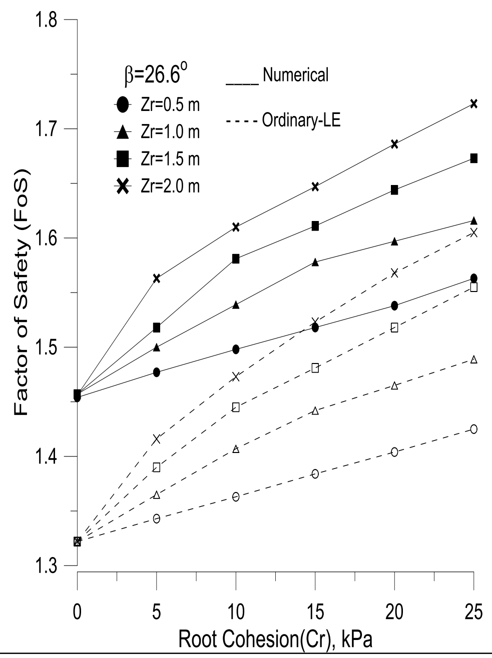


Figure 7: The relationship between FoS and Root cohesion for different values of the depth of the roots for the slope with β=26.6º.

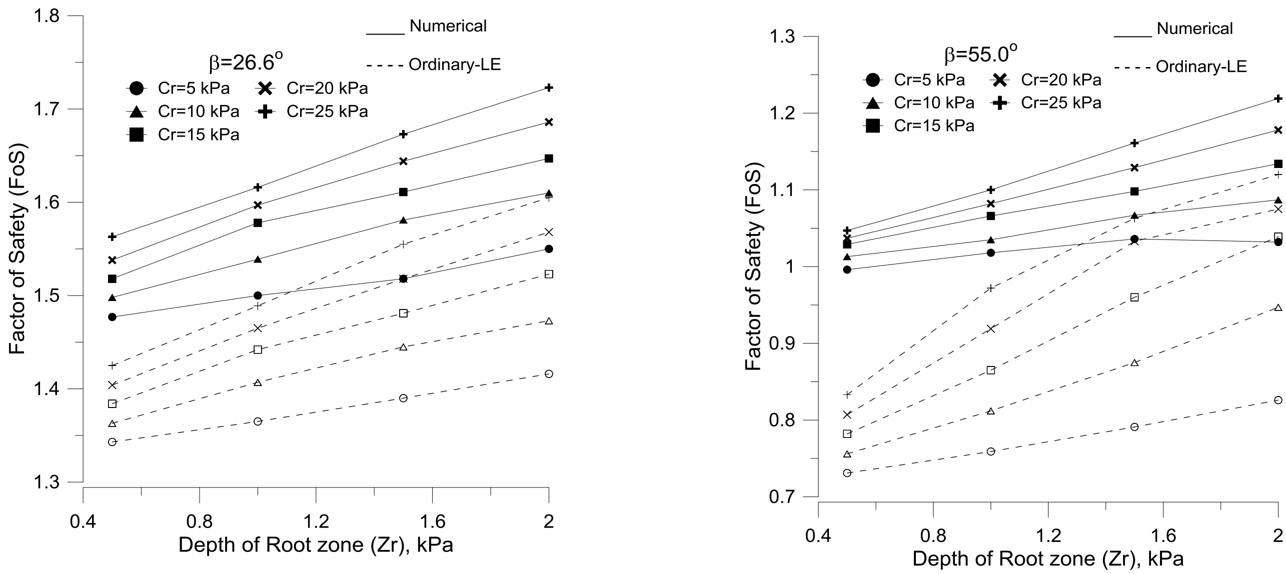
4-3 Effects of Slope Angle (β°)

The results of Table (3) point that the application of vegetation reinforcement can significantly improve the stability of the slopes even in cases with the steep slopes. In comparison for the case with no-vegetation cover, the % of efficiency or the improvement of FoS for the cases with *Cr*=5 kPa and *Cr*=25 kPa, and for all competing slopes (18.4^0 , 26.6^0 , 33.7°, 39.8^0 ,45.0^0 ,55.0^0) are listed in Table (4). These are for the models with the assigned *Zr* of 2m. For the case with *Cr*=25 kPa, the percentage of the improvement of FoS are 13.6 %, 18.3%, 23.0%, 24.1%, 24.6% and 23.9% estimated in these slopes respectively.

Generally, the percentage of increase of FoS for steep slopes are larger than the case with low or flat-slopes. However, and to some extent, this concluding point is backed to the nature of the assumptions adopted for modelling the effects of the vegetation condition by considering a specific Cr value only. This trend in the results and simplifications used to model the impacts of vegetation needs further research especially for the cases with the steep slopes. It is well known that the planting of steep slopes usually faces some difficulties in terms of physical interaction of the vegetation root with the soil structure. Therefore, for modelling purposes there should be a reduction factor for *Cr* value for the cases with steep slopes; or should use other professional software to simulate the more realistic conditions of the vegetation cover.

4-4 Locations of the Vegetation Cover

The numerical results shown in Figure 9 confirm that the direct vegetation of the slope surface is an important action to increase the FoS of the slope. In other words, the slope has a larger FOS when vegetation covers its surface (Cases 1-4) than the crest and toe zones only (Case 5). In addition, the comparison of the cases 3 and 4 reveals that no influence is observed from the toe region vegetation cover.

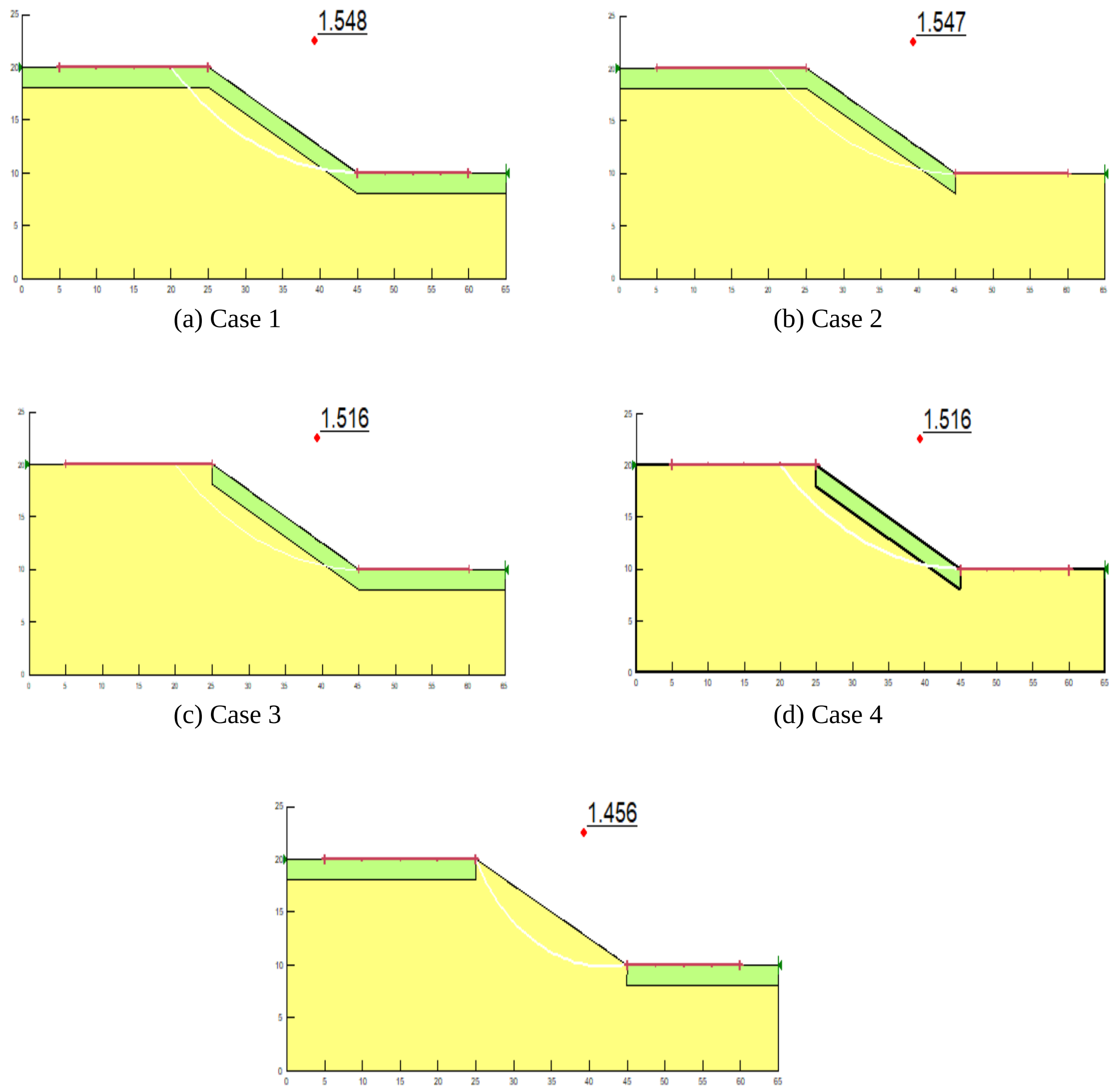


(a) (b)

Figure 8: Effects of the Root Cohesion (Cr) Values on the Stability of the Slopes a) 26.6° and b) 55.0°.

Table 4: Variation of the FoS and its percentage of increase with the inclination angle of the slopes for the cases with Zr=2m.

β°	No vegetation *Cr*=0.0 kPa		*Cr* = 5 kPa		*Cr* =25 kPa	
	Numerical	Ordinary	Numerical	Ordinary	Numerical	Ordinary
18.4°	1.893	1.836	1.979 (4.5%)	1.886 (2.7%)	2.150 (13.6%)	2.025 (10.3%)
26.6°	1.457	1.322	1.550 (6.4%)	1.416 (7.1%)	1.723 (18.3%)	1.605 (21.4%)
33.7°	1.246	1.085	1.350 (8.3%)	1.158 (6.7%)	1.533 (23.0%)	1.398 (28.8%)
39.8°	1.147	0.930	1.239 (8.0%)	1.025 (10.2%)	1.424 (24.1%)	1.275 (37.1%)
45.0°	1.086	0.840	1.159 (6.7%)	0.925 (10.1%)	1.353 (24.6%)	1.234 (46.9%)
55.0°	0.983	0.706	1.032 (5.0%)	0.826 (17.1%)	1.218(23.9%)	1.120 (58.6%)



(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5

Figure 9: The critical values of FoS calculated for different scenarios of the location of the root reinforcement.

CONCLUSIONS

Positive roles of different scenarios of vegetation effects on stability of slopes analysed using both numerical and LE approaches. The main concluding notes from this study are:

1. Application of root reinforcement is a unique economic and environmentally friendly, measure to improves the stability of the slopes. Roots of plants have a potential to mechanically reinforce the soil by increasing its shear strength and thus increase the stability in case of slope problem.
2. The FoS of slopes increases with increasing the depth of roots (Zr) of vegetation that planted on slope. This is due to improving the strength properties of soil resulted by vegetation within this zone (depth Zr). For the slope β=26.6º and with Cr=25 kPa, and in comparison, with the case with no root reinforcement (Zr=0 m), the rate of improvement in numerical value of FoS with increasing the Zr value is about 18.3%.
3. The stability of slopes increases with the increase of the apparent root cohesion (Cr). For the slope β=26.6˚ with the root depth Zr=2.0 m, the rates of improvement of the stability of slopes are 6.4%, 10.5%, 13.0%, 15.7% and 18.3% numerically simulated for the Cr values equal to 5,10,15,20 and 25 kPa respectively.
4. The increase of the slope stability by increasing the properties of the root reinforcement (Cr and Zr values) are observed in the numerical and limit equilibrium results and for all considered inclination angle of slopes.
5. Direct planting of the slope surface results in a larger FoS than crest and toe covered zones. Also, no influence is observed from the toe region vegetation cover.

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