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STABILITY ASSESSMENT OF ROOT-REINFORCED SLOPES USING FINITE ELEMENT LIMIT ANALYSIS

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Abstract

Slope instability poses serious threats to infrastructure and environmental sustainability. As a result, numerous reinforcement techniques have been used as disaster mitigation attempts to prevent slope failure. Among various traditional slope reinforcement methods, the use of vegetion root is more cost-effective and environmentally friendly. This paper presents stability assessment of root-reinforced slopes. Firstly, slope models were built for case of bare and root-reinforced slopes. The slope angles were varied in the range of 15°~55°. The root zone depth and cohesion of root were adjusted within the ranges of 0~1.5 m and 0~20 kPa, respectively. In this study, slope stability was assessed using finite element limit analysis with a strength reduction technique. The results indicate that factor of safety increases with the increasing of root zone depth and cohesion of root. The best factor of safety was obtained for the case with root zone depth and cohesion of root of 1.5 m and 20 kPa, respectively. Shear dissipation contours of the slope models also show that root reinforcement reduces shear dissipation energy along the failure surface, consequently lowering the possibility of slope failure.

Keywords: Disaster Mitigitation, Slope Stability, Root Development, Finite Element Limit Analysis

Introduction

Slope failure is considered as one of the high-risk geo-environmental hazards since it has potential to be harmful, resulting in the loss of human life and damage of properties (Gallage et al., 2021; Xue et al., 2016). Generally, various factors contribute to slope instability such as heavy rainfall (Cho et al., 2021; Yang & Zhang, 2024), earthquake (Farichah & Hutama, 2020; Hutama & Farichah, 2020) or shift of stress condition (Taha et al., 2022). As the results, slope reinforcement is essential in order to mitigate slope failure due to those factors.

Several methods have been used to reinforce the slope such as soil nailing (Ayazi & Tangri, 2021; Goyal & Shrivastava, 2022), anchor (Yoshida et al., 2023; Zhou et al., 2023), geotextile (Broda et al., 2017; Luo et al., 2018), retaining wall (Arbanas et al., n.d.; Bari et al., 2022) and pile reinforcement (Duan et al., 2024; Wang et al., 2023). Among other conventional methods of slope reinforcement, the use of vegetation roots is a cost-effective and environmentally friendly slope reinforcement (Badhon et al., 2021; Ganepola et al., 2021; Ji et al., 2020).

Many researchers have been investigated the effect of root reinforcement to slope stability. Guo et al. (2024) examined how root properties, such as architecture, orientation, and depth, affect the reliability of vegetated slopes during heavy rainfall. Furthermore, Yamase et al. (2024) compared the root system architecture of single and multi-stemmed *E. japonica*, as well as the impact of soil reinforcement on slope stability. Su et al. (2021) studied the effect of root reinforcement on slope stability while accounting for changes in root distribution and tensile strength throughout soil depths. Lann et al. (2024) investigated the hydromechanical effects of plants on slope stability. Moreover, Song & Tan (2024) investigate the microscopic mechanical reinforcing mechanism of plant roots on stabilization of slope. In general, all studies mentioned above have proved that root reinforcement increases stability of the slope.

Essentially, root reinforcement contributes to slope stability by increasing soil shear strength, which is equivalent to an increase in apparent soil cohesion (Cronkite-Ratcliff et al., 2022; Fata et al., 2022). Numerous researchers have conducted extensive evaluations to determine the values of cohesion of root for varied range of plant species living in a variety of environmental conditions. The majority of the results are in the range of 1 to 20 kPa (Chok et al., 2015).

Computational methodologies for slope stability analysis have emerged over the last few decades (Shiau et al., 2023). The limit equilibrium method (LEM) is frequently used in slope stability analysis because it is simple and effective (Schlotfeldt et al., 2018; Siacara et al., 2020). Nonetheless, a critical prerequisite for this technique is an early assumption concerning the slip surface (Peng et al., 2023; Sarkar & Chakraborty, 2021). In the other hand, Finite Element Method (FEM) outperforms LEM in predicting safety factor of the slopes without assuming a slip surface however the analysis requires longer computational time (Ghadrdan & Mokhtari, 2021; Raghuvanshi, 2019). Furthermore, Finite Element Limit Analysis (FELA) has been utilized to assess stability of slopes under different conditions (Oberhollenzer et al., 2018; Yingchaloenkitkhajorn, 2019). This approach can generate two distinct solutions: lower bound (LB) and upper bound (UB) solutions (Poulsen & Olesen, 2024). The FELA approach automates the search for the safety factor, combining the advantages of finite element and limit analysis methodologies. Furthermore, by using adaptive mesh techniques into the calculation, the slip plane can be identified directly (Hu et al., 2024; Zhang et al., 2021).

This study assessed the root reinforcement contribution to factor of safety using finite element limit analysis. The effects of root zone depth and cohesion of root to factor of safety were investigated. Furthermore, shear dissipation contours were used to highlight the root reinforcement effect to stability of slope.

Research Methodology

Slope Geometry

The geometry of slope models for case of bare and root-reinforced slope are presented in Figure 1 and 2, respectively. The height of slope (H) for all cases are 8 m while slope base length (A) are varied depending on the slope angle (β). In this study, the slope angle of slopes models are β=15°, 25°, 35°, 45° and 55°.

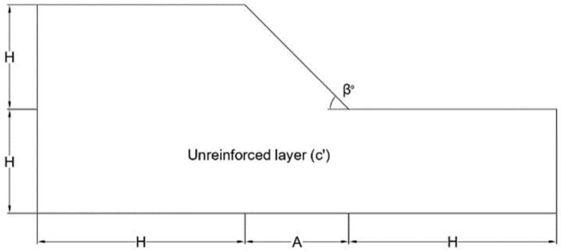

Figure 1. Slope geometry for bare slope

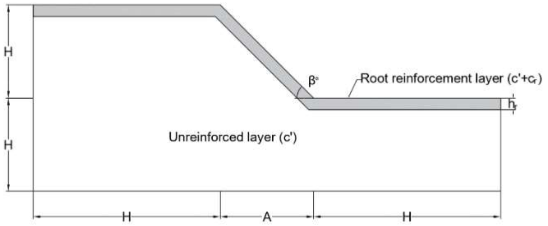

Figure 2. Slope geometry for root-reinforced slope

Input Parameters

Table 1 presents the input parameters used in this study. It should be noted that for condition of root-reinforced slope, the unreinforced layer has only effective cohesion (c'). On the other hand, the root reinforcement layer has effective cohesion and cohesion of root ($c' + c_r$). The slope models are considered to be homogeneous soil slopes. For the case of bare slopes, the parameters of c_r and h_r equal to zero.

Table 1. Input parameters

Parameter	Unit	Value/Range
Unit weight, γ	kN/m^3	18
Effective friction angle of soil, φ'	°	30
Effective cohesion of soil, c'	kPa	10
Cohesion of root, c_r	kPa	0 ~ 20
Root zone depth, h_r	m	0 ~1.5

Strength Reduction Finite Element Limit Analysis

The FELA program (Optum G2) was employed for assessing stability of root-reinforced slopes. The slope models were constructed for three adaptive iterations, with an initial mesh of 5000 elements that was automatically updated and increased to the final mesh. The factor of safety (FS) of both bare and root-reinforced slopes was analyzed using the strength reduction finite element limit analysis. The FS is expressed in relation to material strength, which is the ratio between the strength that is utilized and the actual strength of the material (Sarkar & Chakraborty, 2021; Tschuchnigg et al., 2015).

Research Results and Discussion

Effect of Root Zone Depth to FS

Figure 3 shows how adjusting the root zone depth (h_r) affects the FS of a slope with varied β. The cohesion of root, c_r = 10 kPa and other parameters are kept constant. For all cases of β, it can be observed that the FS increases with h_r. The largest percentage increments in the FS of slopes with β of 15, 25, 35, 45, and 55° when h_r = 1.5 m compared to the case of bare slopes (h_r = 0) are 3.5, 6.8, 10.3, 13.2, and 16.3%, respectively.

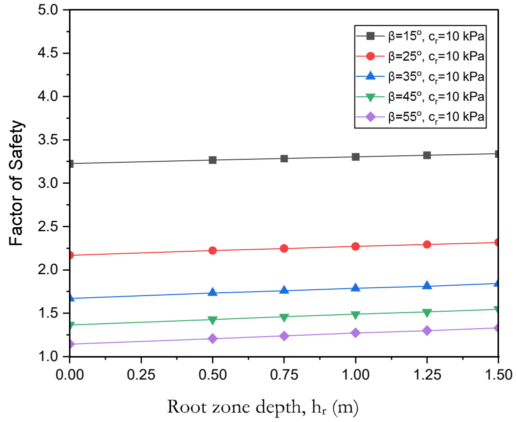

Figure 3. Factor of safety versus root zone depth for c_r = 10 kPa

Figure 4 depicts the plots of factor of safety (FS) versus root zone depth (hr) for slopes with varying slope angles (β). The cohesion of root, c_r = 15 kPa and other parameters are kept constant. When h_r = 1.50 m was applied to slopes with β of 15°, 25°, 35°, 45°, and 55°, the largest percentage increments in the FS compared to bare slopes (h_r = 0) were 5.3%, 9.7%, 14.5%, 18.9%, and 23.1%, respectively.

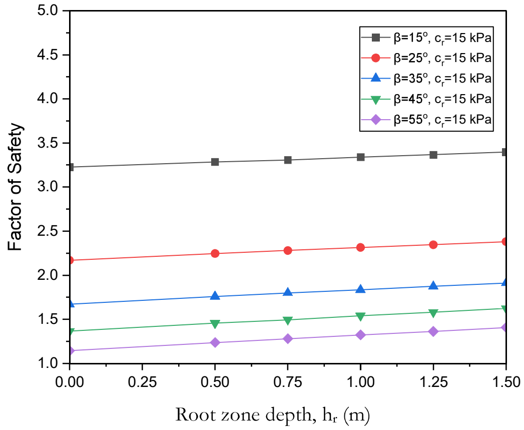

Figure 4. Factor of safety versus root zone depth for c_r = 15 kPa

Figure 5 illustrates the relationship between the factor of safety (FS) and the root zone depth (hr) for slopes with varying slope angles (β), while cohesion of root, c_r = 20 kPa and maintaining constant values for other parameters. The highest percentage increases in FS for slopes with β of

15°, 25°, 35°, 45°, and 55°, achieved when hr = 1.50 m compared to bare slopes (hr = 0), are 6.7%, 12.7%, 18.3%, 23.9%, and 29.3%, respectively. The findings of the study, as shown in Figures 3–5, align with the results reported by Chok et al. (2015) who employed the finite element method. This study concluded that the factor of safety for vegetated slopes increases with the enhancement of root zone depth.

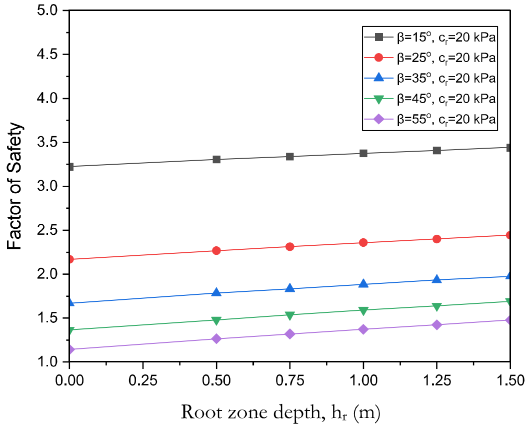

Figure 5. Factor of safety versus root zone depth for $c_r = 20$ kPa

Effect of Cohesion of Root to FS

Figure 6 shows the plots of the factor of safety (FS) versus cohesion of root, (c_r) for the slopes with different slope angle (β), while root zone depth, $h_r = 1$ m and other parameters are kept constant. The presented FS in this study is obtained from average value of lower bound (LB) and upper bound (UB) results. For example, for the case with β = 15°, $c_r = 20$ kPa and $h_r = 1$ m, the factor of safety for lower bound and upper bound solutions are 3.365 and 3.385, respectively. Therefore, the average factor of safety for that case is 3.375.

For all β situations, it is observed that FS increases with increasing of c_r. The maximum percentage increments in the FS of the slopes with β of 15°, 25°, 35°, 45° and 55° which were obtained when $c_r = 20$ kPa compared to the case of bare slopes ($c_r = 0$), are 4.6%, 8.8%, 12.8%, 16.6% and 20.1%, respectively.

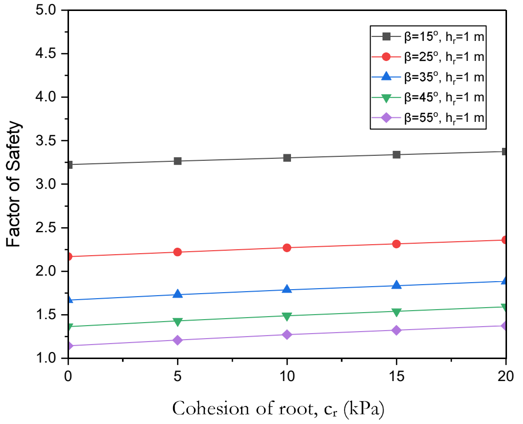

Figure 6. Factor of safety versus cohesion of root for $h_r = 1$ m

Figure 7 depicts the plots of factor of safety (FS) versus cohesion of root (cr) for slopes with varying slope angles (β). Root zone depth, hr = 1.25 m and other parameters remain constant. When cr = 20 kPa was applied to slopes with β of 15°, 25°, 35°, 45°, and 55°, the largest percentage increments in the FS compared to bare slopes (cr = 0) were 5.7%, 10.6%, 15.7%, 20.1%, and 24.6%, respectively.

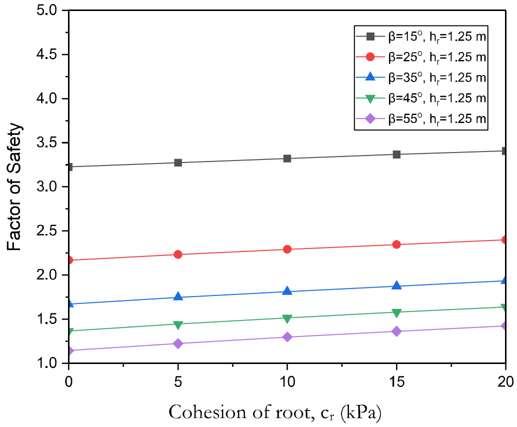

Figure 7. Factor of safety versus cohesion of root for h_r = 1.25 m

Figure 8 depicts the relationship between the factor of safety (FS) and cohesion of root (cr) for slopes with varying slope angles (β), while root zone depth, h_r = 1.5 m and maintaining constant values for other parameters. The highest percentage increases in FS for slopes with β of 15°, 25°, 35°, 45°, and 55°, achieved when c_r = 20 kPa compared to bare slopes (c_r = 0), are 6.7%, 12.7%, 18.3%, 23.9%, and 29.3%, respectively. Figures 6–8 show the research findings, which are consistent with the conclusions given by Chok et al. (2015), who used a different methodology, specifically the finite element method, but their findings are comparable in that the factor of safety for vegetated slopes increases with the increase in cohesion of roots.

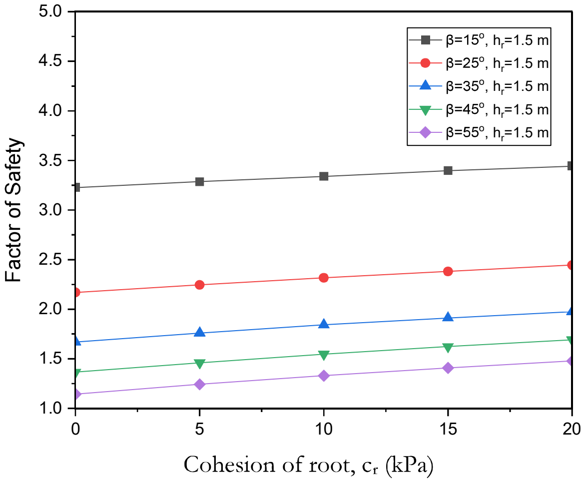

Figure 8. Factor of safety versus cohesion of root for h_r = 1.5 m

Effect of Root Reinforcement of Failure Surface

Shear dissipation contours can be used to present the potential sliding surface obtained from finite element limit analysis. The greater shear dissipation energy indicates a greater shear possibility in the area. Figure 9 and Figure 10 presents the failure surface based on shear dissipation (lower bound) for gentle slope with β=15°, in the case of bare slope and root-reinforced slope with cr = 20 kPa, hr = 1.5 m. It can be observed root reinforcement reduces the value of shear dissipation especially in the failure surface which indicating that the slope model tends to be more stable.

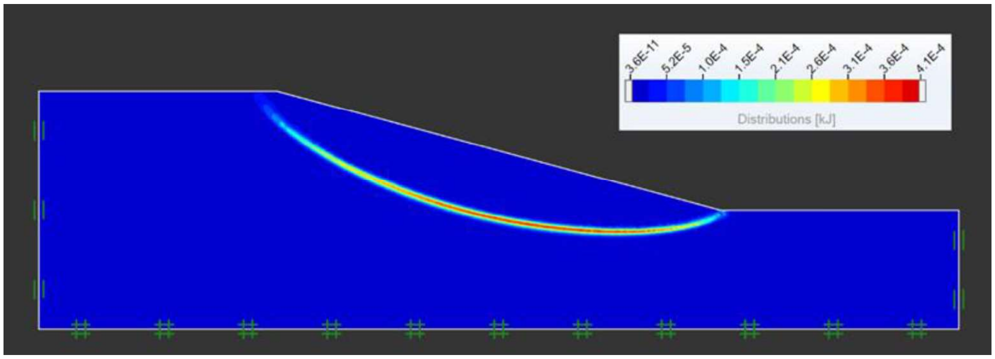

Figure 9. Failure surface based on shear dissipation (lower bound) for gentle bare slope with β=15°

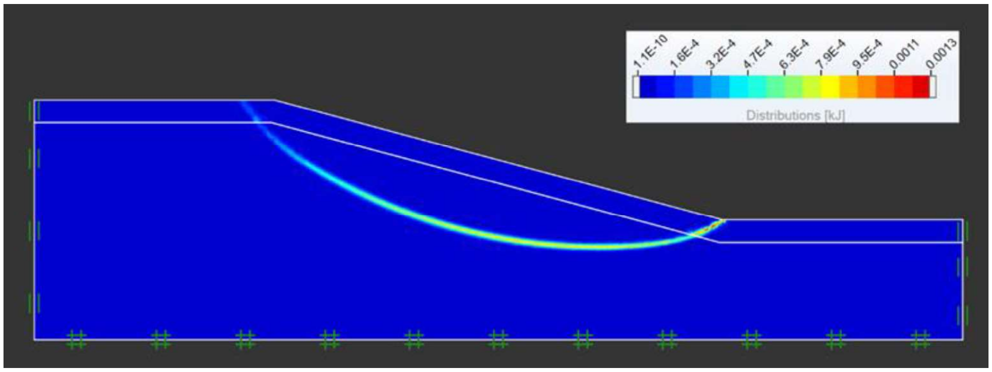

Figure 10. Failure surface based on shear dissipation (lower bound) for gentle root-reinforced slope with β=15°, c_r = 20 kPa, h_r = 1.5 m

Figure 11 and Figure 12 presents the failure surface based on shear dissipation (lower bound) for steep slope with β=55°, in the case of bare slope and root-reinforced slope with c_r = 20 kPa, hr = 1.5 m. The results indicate root reinforcement reduces shear dissipation values, particularly on the failure surface, indicating that the slope model is more stable. The effect of root reinforcement to shear dissipation is more significant for the case of steep slope compared to gentle slope. These results also confirm the previous results which stated that the slope model with slope angle of 55° shows the highest percentage of increment in FS compared to other slope angles.

The results as shown in Figures 9–12 agree with the study of Chok et al. (2015) which proved that the presence of vegetation roots successfully reinforced the slope's weaker zones by providing additional apparent cohesion to the soils and 'pushed' the failure surface deeper into the slope, thereby improving the factor of safety. Additionally, the study of Chok et al. (2015) also concluded that steeper slopes tend to gain more improvement on FS than gentle slopes which is similar to the results of the current study, further validating the effectiveness of root reinforcement in stabilizing steep slopes. Additionally, the effect of root reinforcement on the failure surface of vegetated slopes as shown in this section is also consistent with the findings of Burak et al. (2021), which found that roots reinforce soil by serving as soil pins and dissipating shear stresses. This mechanistic understanding is vital for the development of more accurate predictive models for slope stability in vegetated areas.

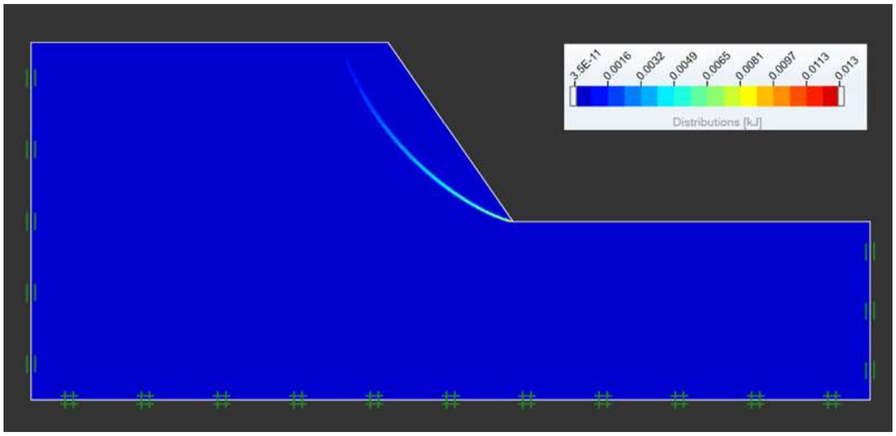

Figure 11. Failure surface based on shear dissipation (lower bound) for steep bare slope with β=55°, c_r = 20 kPa, h_r = 1.5 m

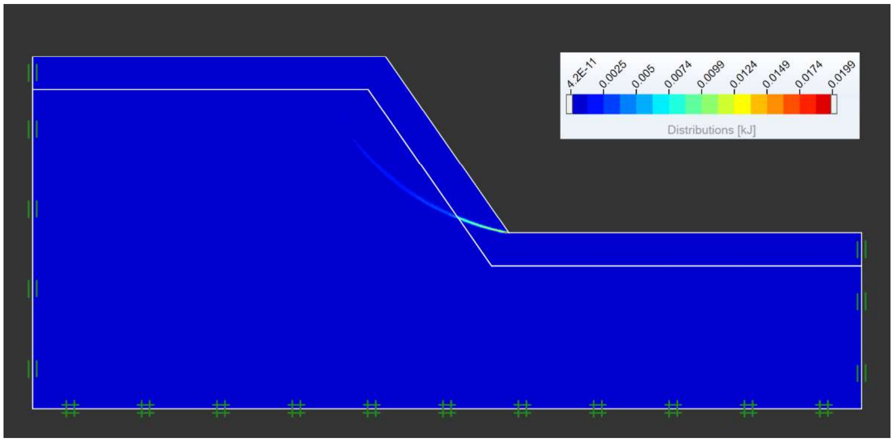

Figure 12. Failure surface based on shear dissipation (lower bound) for steep root-reinforced slope with β=55°, $_{cr}$ = 20 kPa, h_r = 1.5 m

Overall, these findings highlight the critical role of vegetation roots in slope stabilization, particularly for steep slopes. The root reinforcement is proved to be a valuable strategy in geotechnical engineering for managing slope stability in various terrains. This natural reinforcement strategy not only improves safety and reduces the risk of landslides but also supports sustainable environmental practices in geotechnical engineering.

Conclusion

This study used finite element limit analysis to explore the impact of root reinforcement to soil slope stability. Based on the results, several conclusions can be drawn. For all slope models, root reinforcement has been shown to be successful in enhancing slope stability. The best factor of safety is observed for the model with root zone depth (h_r) and cohesion of root (c_r) of 1.5 m and 20 kPa, respectively. Furthermore, the results of factor of safety and shear dissipation indicates that the effect of reinforcement of root to shear dissipation is more significant for the case of steep slope compared to gentle slope. This indicates that in steeper slopes, root reinforcement plays a crucial role in reducing shear stresses, thereby enhancing stability more significantly than in slopes with a gentler incline. This effect can be attributed to the increased demand for stabilization in steeper terrains, where the gravitational forces driving potential slope failures are greater.

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