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THE EFFECT OF SOIL-ROOT INTERACTION BY VETIVER GRASS ON SLOPE STABILITY

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Abstract

The climate of Malaysia, which is hot and humid, has a great impact on soil-root interaction. This study aims to determine the influence of soil-root interaction in slopes, which is calculated in the form of factor of safety. A numerical slope model is studied with Vetiver grass *(Vetiveria Zizanioides sp.)* as the vegetative cover at a residential project in Mutiara Rini, Johor. The mechanical and hydrological effects are measured based on the factor of safety by using the SLIP4EX spreadsheet. The simulation model considers the basic properties of vegetation used and the slope geometry and characteristics. Optimisation on the analysis is conducted by modelling different angles of the slopes (i.e., cut slope ratio) with the presence of groundwater table. Principally, the vegetated slope calculated higher factor of safety by a difference of 5.93% towards the bare slope. The significance of this study indicates that the slope stability can be influenced by the effects of soil-root interaction, different slope angles and existence of groundwater table implemented in the design and construction of man-made slopes.

Keywords: Factor of safety, SLIP4EX, Slope stability, Vegetation, Vetiver grass.

1. Introduction

Over the past decades, Malaysia has been facing many cases of landslides. The natural disaster in fact is one of the dangerous events, which can be fatal, affecting daily activities and damaging residential and commercial structures. Several factors can be taken into account such as the unrestricted deforestation, climate change, abundant rainfall during monsoon, and poor maintenance of man-made slopes. These factors usually influence slope failures to occur gradually. For that reason, it is highly important to tackle these problems at early stage to mitigate the catastrophe of slope failures. In Malaysia, abundant rainfall during monsoon normally induces a drastic change in slope stability. The monsoon happens twice or more each year and the impacts are worse particularly in the East Coast region. A large amount of rainfall intensity normally infiltrates the slope surface depending on the soil permeability.

Rainwater that fails to percolate into the ground will turn into runoff and flows down the slope. These two scenarios (i.e. rainfall infiltration and runoff) are both contributing to the loss of suction in the soil; thus, leading to slope failures. Hence, many of maintenance and protection methods can be applied on slopes such as the applications of vegetative covers, retaining walls, soil nailing and geogrid.

Due to the fact that Malaysia is a tropical country with large trees and averagely-dense forest, the vegetative cover is the best option to optimise its purpose in controlling slope failures naturally. The large trees have strong and non-disruptive grasp of their roots on the ground. Most existing slopes are protected by these trees. Similar principles have been applied on man-made embankments and highway slopes. Vegetative covers usually are planted by the Public Works Department on these cut slopes to reduce slope erosions as well as to protect the slopes which are prone to fail. Hence, the soil-root interaction is significant in the knowledge of using vegetative covers in slope monitoring. Both properties and characteristics of the soil and vegetation involved are to be comprehensively investigated to enhance the protection and maintenance works. Variables for example the type of soils, particles sizes, leaf index and root strengths are the factors that determine the effectiveness of the vegetative covers. Other important variables, which include the ambience or climate factors such as the wind speed, temperature and humidity, can also be taken into consideration. However, strict boundary conditions should be outlined to execute optimisation of the specific method and study its techniques in detail.

This study aims to understand the relationship between soil and root in reinforcing the strength in slopes. Different soil and root properties and characteristics are used in the parametric analysis to determine the effectiveness of the vegetative cover in slope protection. Also, the slope geometry (i.e., slope angle) is further studied to acknowledge the effects of design and construction of cut slopes. Final results are presented in factor of safety (FOS) for different conditions of the slopes applied. Vetiver grass has been chosen as the vegetative cover and its properties and characteristics are described. By establishing the soil-root interaction in terms of mechanical and hydrological effects, the slope failure can be controlled by calculating the factor of safety. The significance of the study highlights the importance of selecting an appropriate vegetation type and investigating its features for the purpose of slope protection and maintenance.

2. Vegetation

The approach of using vegetation as the slope cover has several advantages inclusive of environmentally friendly, low maintenance, self-sustainability and high biodiversity [1]. Coppin et al. [2] further added that the advantages of vegetation are self-repairing, regenerating and adaptive. This will ease the work of maintaining the vegetation on the slopes. As the vegetation behaves greatly in adaptation, the root structure will grow well to fit in with the ground soil as it acts as the vegetation habitat.

Vetiver root has proven to be living soil nails or dowels that can pin the soil together. It has the root strength by the average of 75 MPa [3]. This vegetation root improves the shear strength of soil at 0.5 meters deep by as much as 40 percent. The major advantage of Vetiver root over other grass roots is that they penetrate the soil profile going straight down vertically and do not spread laterally to compete with companion crops for nutrients. Vetiver grass also can withstand rainfall up to 600 mm per annum and regrow rapidly due to drought, frost, fire, saline and other climatic conditions [3]. Vetiver hedgerows have been demonstrated in Malaysia, Thailand, Australia, and China to be a relatively low-cost and effective means of stabilizing highway and railroad cut and fill slopes [4].

Wu et al. [5] critically reviewed the bioengineering process that is making use of plants in enhancing soil stabilisation against erosion and failures. They also studied the numerical methods by means of limit equilibrium and finite element codes to model the behaviour of soil roots upon the soil stabilisation. Moreover, Preti et al. [6] analytically studied the hydrological, pedological and above-ground vegetation aspects to provide a preliminary assessment of incremental cohesion by plant roots. Their findings are highly potential in soil bio-engineering and large-scale analysis of vegetated slope stability. In slope stability analysis. Figure 1 shows the diagrammatic feature of soil reinforcement using Vetiver grass. The long roots contribute to the stability on the slope by minimising the mobilisation of failure surface.

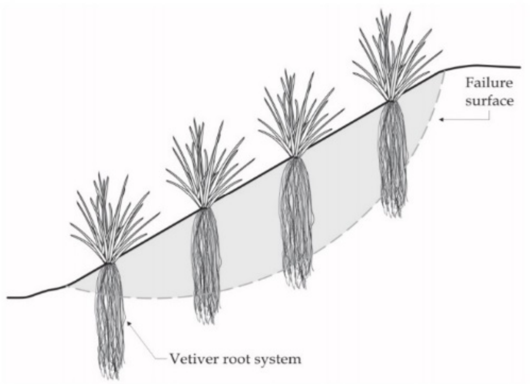

Fig. 1. Vetiver grass applied for slope protection [7].

3. Root tensile strength

Plant roots mechanically increase soil shear strength by transferring shear stress from the soil into tensile forces of the roots themselves. This mechanism happens via the interface friction along the root surface. The same concept is used in the method of soil nailing which routinely applied in the geotechnical and environmental engineering. However, the reinforcement of the root is influenced by the orientation and geometry of the root relatively to the shear force, skin friction and material properties of the roots as well as area of the shear plane occupied.

Kokutse et al. [8] studied the influence of roots systems by modelling the corresponding values of additional cohesion distributed through different soil layers of the root zones. It is challenging to measure these aforementioned variables but they are highly essential in order to develop a good root reinforcement model. Under the effects of vegetation, the slope stability is influenced by the root morphology, density and mechanical properties. For instance, fine or medium roots within the range of 0.1 - 10 mm diameter may traverse the potential shear surface of a slope. Consequently, the soil is reinforced and pinned into place whereas the ticker roots (i.e., more than 10 mm) diameter will behave like soil nails. Therefore, high values of root soil strength are preferred as it increases the soil reinforcement.

Genet et al. [9] also investigated the effect of FOS based on vegetated and bare slopes. They discovered that the FOS is varied not just by the root reinforcement but also the weight of large trees contribute as surcharge on the slopes. FOS is higher when the tree is located at the toe compared to the crest. They mentioned that different species of plant will not make major difference to the FOS than the position of the tree on the slope.

4. Hydrological effect

Many literatures have analysed and reviewed the mechanism of rainwater infiltration into the soil causing the instability of slopes [10-14]. Mukhlisin et al. [15] also added that the degree of saturation is increased upon rainfall infiltrations, which reduced the negative pore-water pressure directly. As a result, shear strength of the soil is decreased and the slope is highly risked of failure. The accuracy of measuring the moisture content has significant effects on the FOS due to the substantial influence of suction in the soils.

The hydrological effect of vegetation on the slope stability can be studied by the removal of water from the soil through the process of evapotranspiration [16]. The process allows for the development of soil suction and thus increases the soil shear strengths. Additionally, the process also reduces the soil's moisture content and the evaporation by the plants reducing the mass weight of the soil. Therefore, the hydrological effect by means of groundwater flow in the soils due to the effect of evapotranspiration and transpiration contributes to the increase of soil shear strength, and reduces the possibility of slope failures.

Osano [17] found an increment of tensile strength in vegetation roots at high strain during landslide due to high resistance forces, which provide high factor of safety. Charlafti [18] also investigated the effect of vegetation on slope stability using the extended Mohr-Coulomb failure criterion for unsaturated soils. He discovered that the increased effective angle φ_b allows for higher factor of safety recorded. This advanced unsaturated model is popular in numerical modelling of unsaturated slope boundary problems and enhanced the development of research in partially saturated soils.

5. SLIP4EX

In order to determine the mechanical and hydrological effects of grass on the soil, SLIP4EX spreadsheet can be used. SLIP4EX is an easy access program that assists in understanding the soil-root interaction and also providing a slope stability analysis. For the benefit of beginners in numerical modelling, SLIP4EX is a recommended program as it facilitates the users to recognise the calculation process in slope stability analysis before employing other complex modelling packages. Several research also adopted the spreadsheet such as the work by Osiński et al. [19] that studied the effect of six different characteristics (i.e., slope height and angle, vegetative cover, applied surcharged, position of groundwater table and soil mechanical conditions) on slope using SLIP4EX. Moreover, the program is valuable for student learning courses due to the fact that the design procedures of drawing the slope geometry, selecting the slope surface and allocating all the appropriate analysis parameters are under the user's control. The program estimates the slope stability and compares the factor of safety using the methods by Bishop, Janbu, Greenwood, Simple and Fellenius. The analysis also includes soil reinforcements by the application of geosynthetic layers or anchors, and vegetation effects of enhanced cohesion, changed pore-water pressure, mass of vegetation, wind speed and root reinforcement forces. This program enables a simpler and easier technique to understand the nature of analysis, regulate the assumptions of parameters and compares the different procedure of each method.

6. Scope of study

In this study, the effects of tree root on the stability of a slope were studied. The simulation using SLIP4EX were used. A group of tree comprises of the same species were assumed positioned at the toe, middle-height and crest of the slope. The properties of the trees were taken into account by means of physical and growth characteristics such as the root size. The FOS percentage difference is investigated with various cut slope ratio (i.e., 1.5/1, 1/1, 1/1.5, 1/2.0 and 1/2.5) for different root diameters such as 0.7, 0.75 and 0.8 mm. In addition, the soil used in the study was sandy material. The properties of the soil are described in the next sub-section. The effect of groundwater also was studied by applying the groundwater table at the slope. The effects were mainly compared with the non-existence of groundwater table. Other ambience and environmental factors for example the rainfall, humidity, temperature and other climate variables are not considered to maintain a focus boundary in understanding the efficiency of root reinforcement in slopes. For the analysis of the effect of groundwater table, the method of analysing was conducted by three different techniques for example the Greenwood General, Greenwood Simple and Swedish methods.

6.1. Soil properties and slope geometry

The soil used in the analysis was sandy material. The soil properties are presented in Table 1. The existing slope geometry was referred to the existing slope of a residential project in Mutiara Rini, Johor as shown in Fig. 2. Based on the geometry, a number of different slope angles were used in this study as parametric analysis to determine the influence on slope stability. The original angle was 34^0 given by a ratio of 1.5:1 for a length of 1:3 metres. Other angles were extended at 1:1.5 for the steepest slope of 56^0, followed by 1:1 for 45^0, 2:1 for 34^0 and 2.5:1 for the least steep slope at 27^0.

Table 1. Test model specifications and test conditions.

Properties	Sand
Unit weight, γ (kN/m^3)	18
Cohesion, c (kN/m^2)	13.3
Angle of friction, θ	0

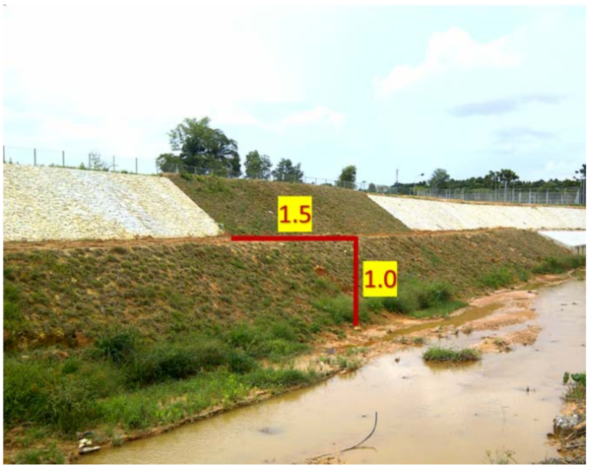

Fig. 2. Existing slope geometry in Mutiara Rini, Johor.

6.2. Tensile root strength contribution, T

The root force acting on the base of each slice is calculated by, = T_{rd} x l. The T_{rd} is the available root force per square meter of soil and l is the length of the slip surface. Based on the data gathered by Greenfield (2002), four roots within the range of 0.70 mm to 0.80 mm diameter are assumed to have an ultimate pull-out resistance of 75 MN/m^2 each. For example, the ultimate root force per square meter across the slip plane, T_{ru} can be calculated with an average root diameter of 0.75 mm as follows:

T_{ru}=4π ×0.000752 × 75 × 1000/4 = approximately 0.133 kN per square meter of soil.

By applying a partial factor of safety of 8 to allow for uncertainty in root distribution and incompatibility of failure strain between the root and the soil (Greenwood et al., 2003), the design root force per square meter, T_{rd}, is given by T_{ru}/8 and the calculated T_{rd} = is 0.0166 kN/m^2. Coming back to the root forces, T, an example of the cur slope ratio 1.5:1 with 0.75 mm diameter, T is calculated at 0.0175 kN.

6.3. Effective angle between operational roots and slip surface

The effective angle, θ between operational root and slip surface is the angle of grass in diagonal towards the ground surface. It is conservative to adopt a 45^0 angle in relation to the effect of shearing. In the analysis, however, different angles based on the ratio of the cut slope were used to impersonate wider design criteria such as 1:1.5 with 56^0, 1:1 with 45^0, 1.5:1 with 27^0 and 2.5:1 is 25^0. The parametric studies on geosynthetics and root reinforcement indicated that the calculated resistance due to root strength is not subjected to the sensitivity of the effective angle only because when the enhanced normal component acting across the slip surface reduces, the tangential component increases [20, 21].

7. Results and Discussion

For slope profile simulation without the effect of groundwater table, the root diameter selected in this analysis was taken at 0.75 mm as an average value. The results were compared in between the factor of safety with vegetation and without vegetation. The percentage difference is used to indicate the effectiveness of the vegetation as contributing factor in the slope protection method.

7.1. Effective of vegetation

In this section, the results calculated using all methods (i.e., Greenwood General, Greenwood Simple and Swedish) demonstrated same FOS values. Therefore, the results discussed here may represents any of the methods adopted. The FOS for bare and vegetated slopes are shown in Fig. 3(a) whereas the FOS difference (in percentage) between the two conditions are shown in Fig. 3(b). From Fig. 3(a), it can be seen that the FOS are lower for cut slope ratio 1:1.5. This is because the slope is at an angle of 56^0, indicating a very steep slope. The low FOS may have been influenced by a weak soil – root interaction because of the slope angle too. The other cut slope ratios are higher due to the fact that the slopes were gentle with 45^0, 27^0 and 25^0. These differences can be explained by the effective angle between the grass roots and the ground surface as gentler slopes may have induced better stability supported by the strong hold of the plant roots. Schwarz et al. [22] discussed the role of lateral root reinforcement quantitatively in vegetated slope. They quoted by neglecting the lateral root reinforcement, landslide would occur as the FOS may reach lower than 1.0.

On the other hand, Fig. 3(b) shows that the difference between the slope conditions (i.e., bare and vegetated surfaces) is not large. All the percentage difference are found less than 10%. The smallest difference is shown by the cut slope ratio of 2.5:1 with 25^0 angle. With this ratio, the slope is most stable; however, it must be reminded that if the slope were to be constructed with gentle slope angle, larger area of the slope are needed and the cost will be higher. In addition, cut slope ratio of 1:1.5 with 34^0 angle should be avoided too since the difference is the highest. Therefore, an ideal slope design considering the effect of soil-root interaction is best chosen either at 45^0 or 27^0 angle. It is important to highlight that the effective angle offers high shear resistance and tensile strength of the root on the ground soil. Cazzuffi et al. [23] studied the effect of different diameters of the plants root on soil shear strength and found that smaller diameters contribute to higher soil shear strength. Since the diameter of grass used in this study is averagely small, this criterion is best to be investigated further in terms of vegetation varieties such as type, size and length, and tensile strength to conduct better slope stability studies.

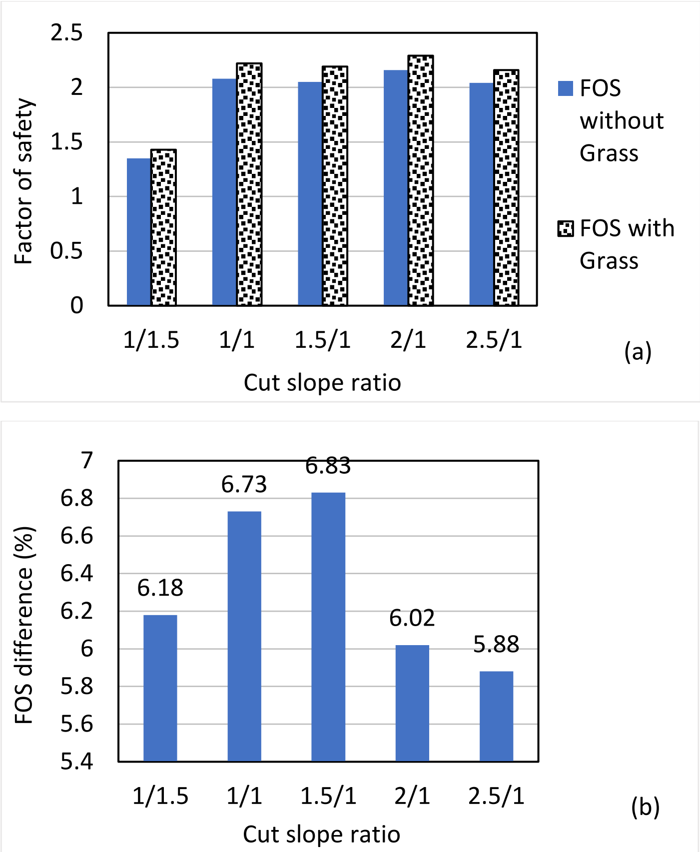

Fig. 3. (a) FOS against cut slope ratio,
(b) FOS difference against cut slope ratio.

7.2. Different calculation method

The FOS generated with the effect of groundwater table in this section was calculated using three different methods. They were the Greenwood general, Greenwood Simple and Swedish methods. Figure 4 shows the percentage difference of FOS calculated by the three aforementioned methods. From the chart, it can be seen that the Greenwood General calculated the highest percentage difference particularly at the cut slope ratio of 1:1. The next highest is the Swedish method for slope ratio 2.5/1. By comparing these two ratios, 1:1 (i.e., 45^0) is more economical design compared to the 2.5/1. Having said that, the slope with 45^0 is the most common angle implemented whereas the construction of gentler slope may require larger area and costly. Moreover, Greenwood General computed the best result due to the fact that the equations include all the slices and water table parameters in the calculations. These conditions suggest that the root reinforcement was behaving at its optimised state under the exposure of soil moisture content as well as the effect of suction.

For Greenwood Simple method, the highest value it can calculate is only 7.84% at the same cut slope ratio (i.e., 1:1) with the Greenwood General method. The low percentage can be explained by the groundwater table allocated for each slice of the method. The water contained in the ground has not been distributed equally within the slices. The breadth of the slices may affect the calculation by means of the effectiveness of the root reinforcement. Therefore, the percentage difference calculated by Greenwood Simple is small when FOS with vegetated grass does not grow properly. Furthermore, the Swedish method shows an average percentage difference of factor of safety as compared to the other two methods. The Swedish method assumes that the groundwater table is parallel to the slip surface. For cut slope ratio of 2.5:1, the result shows the largest percentage difference unlike the other two methods that were optimised at cut slope ratio of 1:1. The 2.5/1 slope is considered a gentler slope and the water level, which is parallel to the slip surface, does not intervene with the slope stability. Suctions in the unsaturated zones induces more strength to the soil. Moreover, the small angle contributes highly to the slope stability. Therefore, it is shown that smaller angle of slope gives higher difference of FOS.

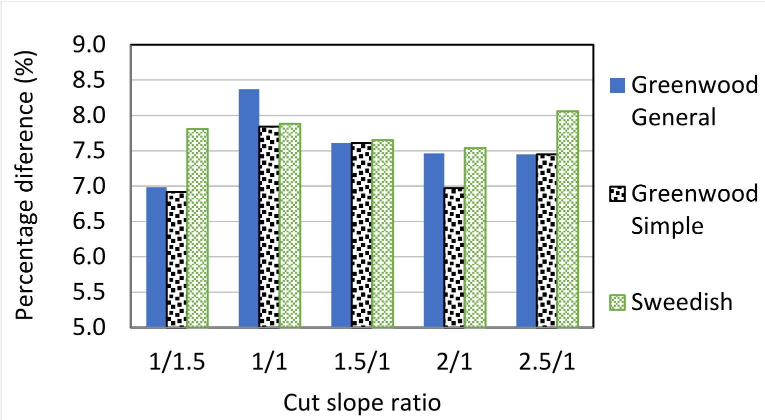

Fig. 4. FOS difference against cut slope ratio using three different method of calculations.

7.3. Effect of groundwater table

Figure 5 presents the comparison between the FOS difference (%) with and without the effect of groundwater level. As shown in the chart, the FOS difference with the effect of groundwater level are lower compared to the difference without the groundwater level. The highest difference with the groundwater is observed for the cut slope ratio of 1.5/1. The second highest is recorded for 1/1 with minor difference at 0.1%. On the other hand, the highest difference under the effect of groundwater is at the ratio of 1/1. It can be explained that at this angle (i.e., 45^0), the soil-root interaction have performed highly effective due to the contribution of effective angle and the influence of the groundwater. The effective angle may induce even distribution of water particularly at the middle height of the slope and this has allowed for the vegetation roots to develop well. Consequently, the root reinforcement could yield improved strength and aided to better slope stability. By adopting to design a steeper slope (i.e., 45^0) compared to less steep angles, the design of the slopes can be implemented economically, high aesthetic and environmental friendly.

From this comparison, it can be suggested that the FOS with groundwater has low FOS in general. The effect of water reduces the soil shear strength by means of reduction in suction. Therefore, the development of negative pore-water pressure reduces. In terms of the FOS difference, although the percentage are lower with the effect of groundwater, it does not mean that the soil-root interactions has low efficiency in providing root reinforcement. The overall results in fact has proven that the FOS is higher with the influence of root reinforcement.

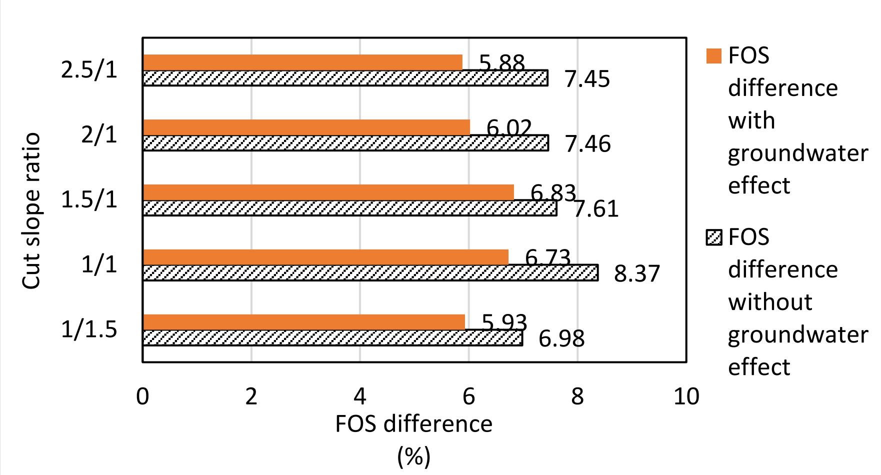

Fig. 5. Percentage difference for FOS with and without the effect of groundwater.

8. Conclusion

To conclude, the root force of three different Vetiver grass diameters is reliable for SLIP4EX simulation. Based on mechanical effect, cut slope ratio of1.5:1 slope gives the largest FOS difference of 6.83%. While for hydrological effect, the highest FOS difference is 8.37% with cut ratio of 1:1 simulated by Greenwood General method. The overall results have proven that the root reinforcement influenced a high FOS. This outcome is presented by the vegetated slope, which calculated FOS of 1.43 with difference of 5.93% towards the bare slope. All the results recorded in this analysis with different cut slope ratios and groundwater table effects, revealed that the FOS with the effect of vegetation is higher compared to the FOS without vegetation. Also, the slope with presence of ground water demonstrated lower FOS because the soil suctions is affected thus reducing the soil shear strength.

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