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Stability Analysis of Plant-Root-Reinforced Shallow Slopes along Mountainous Road Corridors Based on Numerical Modeling

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Abstract: Engineering methods such as soil nails, geosynthetic reinforcement, retaining structures, gabions, and shotcrete are implemented to stabilize road cut slopes along mountainous areas. However, these structures are not environmentally friendly and, particularly in Ethiopia, it is impossible to address all road problems due to financial limitations. Nowadays, soil reinforcement with plant roots is recognized as an environmentally sustainable alternative to improve shallow slope failure along mountainous transportation corridors. The aims of this study was, therefore, to conduct slope stability analysis along a road corridor by incorporating the effect of plant roots. Five plant species were selected for the analysis based on their mechanical characteristics. Namely, *Eucalyptus globules* (tree), *Psidium guajava* (shrub), *Salix subserrata* (shrub), *Chrysopogon zizanioides*, and *Pennisetum macrourum* (grasses). The roots' tensile strength and soil parameters were determined through tensile strength testing and triaxial compression tests, respectively. The factor of safety of the slope was calculated by the PLAXIS-2D software. The study showed that when the slope was reinforced with plant roots, the factor of safety (FOS) improved from 22–34%. The decreasing effect of vegetation on slope stability was observed when soil moisture increased. The sensitivity analysis also indicated that: (1) as the spacing between plants decreased, the effect of vegetation on the slope increased. (2) Slope angle modification with a combination of plant roots had a significant impact on slope stabilization. Of the five-selected plant species, *Salix subserrata* was the promising plant species for slope stabilization as it exhibited better root mechanical properties among selected plant species.

Keywords: numerical modeling; plant species; roots; slope stability

1. Introduction

Plant roots can efficiently improve the soil shear strength of the slope and forms the root–soil composition of the nearby surrounding soil. The roots of vegetation are intermingled in the soil layers of the slope, making the soil of the slope a combined layer [1–5]. The mechanism through which root-reinforced soil is related to concrete reinforcement mainly plays the role of shear stress and tensile strength effect. The effect of root reinforcement increases the cohesive strength of soil, decreases soil deformation, prevents the incidence of surface tension cracks, and can avoid slope failure initiated by triggering factors [6–16]. The shear stress is developed in the soil and transferred to the ground as tensile resistance in the roots, which ensures mechanical reinforcement by the roots [17–24].

The effect of plant roots on slope stability can be divided into hydrological and mechanical factors, which can be valuable to ensure slope stability [1,2,5,21,25–37]. With regards to the hydrological effects, plants intercept rainfall allowing it to slowly infiltrate into the soil by reducing the runoff velocity and, thus, reduces soil erosion [7,8,38]. Additionally, vegetation can reduce soil moisture by means of transpiration, which increase the matrix suction of the soil, resulting in an increase in the soil shear strength [7,14,37]. In terms of mechanical aspects, vegetation increases the soil shear strength by transferring the shear stress developed in the soil to the roots fibers, through the tensile strength mobilized in the roots [39–42]. This study focused on the mechanical effect of plant roots on slope stabilization along mountainous transportation corridors by considering the effect of soil moisture variation.

In recent decades, a few powerful design tools have been created for slope stability analysis. The advanced technology has increased the use of finite element (FE) methods as it dominates a wide range of features. Geometry is discretized into finite elements. It also incorporates the effect of material stiffness in the analysis and can model non-linear stress–strain behaviour of materials and understand their stability on the basis of deformation characteristics. The finite element method can be used to assess the stability of slopes using a failure definition, such as the finite element strength reduction method. In the strength reduction method, soil strength parameters is reduced until the slope becomes unstable and, thus, the factor of safety is calculated as the ratio between the initial strength parameter and the critical strength parameter [13,41,43–51].

Chock et al., [33] conducted a slope stability analysis using the FE method. From the analysis, they reported that the computed factor of safety (FOS) was 1.05, without root reinforcement, which showed that the slope was marginally stable. When the plant was grown on the entire slope, the FOS increased from 1.05 to 1.25, indicating a 19% improvement in stability. The factor of safety (FOS) increased to 1.2 (14.3%) as the vegetation was grown on the surface and toe of the slope. However, when the plants grew only on the surface of the slope, the FOS was increased by only 3%. The FOS of the slope depended on the increment of the root cohesion (C_r) value and the depth of root (H_r). Similarly, Naghdi et al. [2] found that when plants vegetated on the entire slope, the FOS increased significantly than when vegetation grew only on the slope toe, slope surface, on the top of slope. On the contrary, Habibah et al., [10] stated that when a hillslope was vegetated with trees at the bottom of the slope, it became more effective in slope stabilization than at any other position on the slope. To investigate the contradictions between the previous studies, the spatial distribution of vegetation on the slope were conducted and compared among the selected plant species.

Slope failure disasters are an universal occurrence on a planet that, like Earth, is tectonically active [7,15–17]. Slope failure along road corridors is one of the critical problems in the mountainous terrain of Ethiopia. The losses by landslide in Ethiopia that occurred between 1993 and 1998 destroyed more than 200 houses, more than 500 km of roads, and caused the death of about 300 people. Slope failure problems in Ethiopia are mainly related to hilly and mountainous terrains of the highlands of Ethiopia, which is characterized by variable topographical, geological, and hydrological and land use conditions. Earthquake-triggered landslides are rarely reported in Ethiopia. Landslide related hazards are becoming thoughtful concerns to the public and to the planners and decision-makers at various levels of the government [6].

In the case study area, the Jimma-Mizan asphalt concrete road, passes through the irregular topography of the south-western part of Ethiopia. The rugged geographical condition that is accompanied by the erratic rainfall leads to repeated slope failure along road corridors. This causes loss of human life, hindering of traffic movement, high maintenance cost, and destroys infrastructures. This led to the necessity of an investigation of slope safety along road corridors. Mechanical slope retaining structures are being implemented to stabilize slopes prone to failure. However, these structures are not environmentally friendly and it is not possible to address all of the road problems, due to financial limitations [52]. Thus, the use of plant roots is considered a sustainable alternative to improve slope stability. However, there are no studies that have been conducted on the mechanical characteristics of vegetation to stabilize cut slopes along mountainous road corridors in Southwest Ethiopia.

Therefore, the objective of this study is to conduct slope stability analysis by considering spatial distribution of vegetation along the road cut slopes using numerical modelling, evaluate and select suitable plant species for slope stabilization. In addition, the parametric study is conducted to assess the sensitivity of a factor of safety of the slope to the different species of plants, variation in soil moisture content, vegetation spacing and geometry of the slope.

2. Materials and Methods

2.1. Topography of the Study Area

The study site is characterized by highly variable topographic features. In which, the steep hill slope and deep cut valley are dominant in the area. Since the hill slope are steep enough, external factors such as rainfall and road cut could trigger the slope to failure. As well, the land use land cover also potential for instability of slope in the study area. Less vegetated hill slope of the area also aggravates to slope instability than vegetated slope, which ensures less mass wasting process [27]. The depth of failure plane of the slope is variable, which ranges from 0.5 m to 2 m. As shown from Figure 1, the mode of failure is earthen slide and mudflow with shallow soil cover.

Figure 1. Mode of failure of study area, earth slide (**left**) and mudflow (**right**).

2.2. Study Area

This study is conducted in the sub-humid tropical area along Jimma-Mizan asphalt concrete road, South-western Ethiopia. It is located 430 km to the South-western of Addis Abeba, wich is capital city of Ethiopia. The study area is located between 7°27′25″ to 7°30′00″ latitudes and 36°24′55″ to 36°27′25″ longitudes (Figure 2).

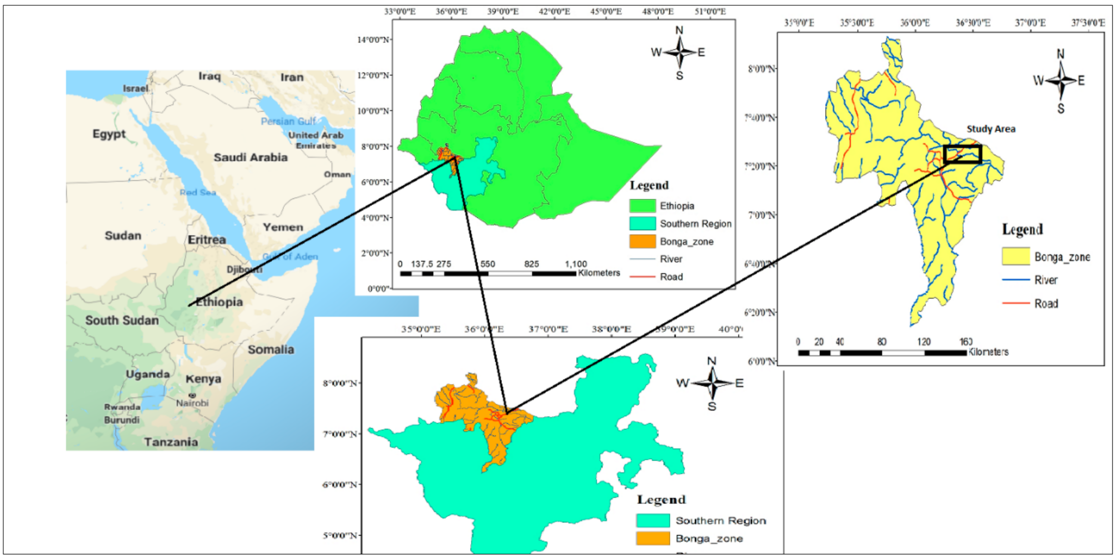

Figure 2. Map of the study area.

The area characterized by a significant rainfall lasting from May to end of September. The rainy phase peaks from July until the beginning of September and the average annual rainfall of study area is 1650 mm/year.

2.3. Sampling and Root Excavation Techniques

Five plant species were selected for root characterization and tensile strength test. The root excavation of each plant species were carried out manually within the area delineated by the vertical projection of the above ground biomass [52] and to various root depth (Figure 3). The size of excavated area is a function of the width of the above ground biomass in each plant species. During excavation, care was taken to avoid any damage to roots. After excavation, the roots were packed immediately in plastic bags to preserve their moisture content and then transported to the Jimma University Institute of Technology for tensile strength tests.

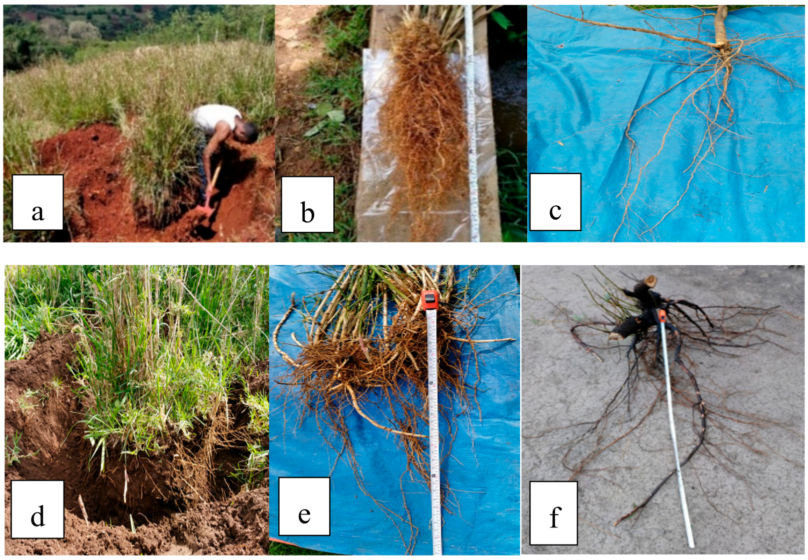

Figure 3. Selected plant species ((**a**) = root excavation for *Chrysopogon zizanioides*, (**b**) = root system for *Chrysopogon zizanioides*, (**c**) = *Psidium guajava*, (**d**) = root excavation for *Pennisetum macrourum*, (**e**) = root system for *Pennisetum macrourum*, (**f**) = *Salix subserra*).

2.4. Selection of Plant Species

Selection of appropriate plant species for rehabilitation of degraded land and slope failure is based on their promising mechanical root characteristics [53]. Five plant species, namely, *Eucalyptus globules* (tree), *Psidium guajava* (shrub), *Salix subserrata* (shrub), *Chrysopogon zizanioides* and *Pennisetum macrourum* (grasses), which are the most dominant and native to the study area were selected. *Salix subserrata* is the species growing fast, regenerating itself, and characterized by deeply penetrating tap root system with lateral thin roots. *Chrysopogon zizanioides* and *Pennisetum macrourum* are widespread grass species, which are characterized by a shallow root system with relatively short tap roots. *Eucalyptus globules* is a tree species which develops deep taproots with long lateral roots, and which generates a large root system with relatively short taproot and long lateral roots [53,54]. As for *Psidium guajava*, the roots of this species possess very thin and numerous roots with horse tail-like thin roots, where each of secondary and tertiary roots develops several smaller roots to anchor the alluvial soils near rivers [54]. Therefore, the unique characteristics of roots makes the species a very promising candidate for slope stabilization along transportation corridors in sub-humid tropics like south-west Ethiopia.

2.5. Determination of Root Tensile Strength

Five plant species are selected to test the tensile strength of roots for the proposed slope stability analysis model. The test was conducted for different root diameter ranges between 0.25–6.5 mm. To ensure an accurate reflection of the mechanical roots property, all plant root specimen, which were collected from the field, were placed in sealed bags. The tensile test was done by using a Testometrics material-testing machine (serial no. 500–517, Testometric Co.Ltd, London, UK) with the test force ranges between 40–100 KN with testing speed of 20 mm/min. The root diameter was measured using digital calliper in three different points, and the mean diameter was calculated to assign the representative value corresponding to the breaking point of each sample. The tensile strength value of each root was determined by the machine load cell and recorded with the data logger. The influence of roots on the reinforced strength of soil can be expressed as a cohesion term [5] in the Mohr-Columb failure criteria determined by Equation (1):

$$S_r = C' + (\sigma - \mu) \tan\varphi' + \Delta S \tag{1}$$

where C' is the effective cohesion of the soil, σ is the normal stress due to the weight of water and soil of sliding mass, μ is pore–water pressure developed in the soil, φ' is the effective friction angle of the soil and ΔS is the apparent cohesion provided due to the presence of roots. According to the study conducted by Genet et al., [5] the additional soil cohesion provided by plants root can be calculated by Equation (2):

$$\Delta S = T_r\ A_{ri}|A\ (sin\beta + cos\beta tan\varphi') \tag{2}$$

where T_r is the average tensile strength of roots per unit area of the soil, $A_r|A$ is root area ratio (%) and β is the angle of root distortion in the shear zone. Sensitivity analyses shows that the values of ($sin\beta$ + $cos\beta{\cdot}tan\varphi'$) can be approximated as 1.2 for $30° < \varphi' < 40°$ and $48° < \beta < 72°$ [5]. The following formula was used to calculate the tensile strength as stated in Equation (3):

$$T_r = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)} \tag{3}$$

where, F_{max} is the maximum force (N) needed to break the root and D is the mean root diameter (mm) before the break.

The model developed by De Baets et al. [35] is used to estimate the increase in soil shear strength due to presence of roots. Their model assumes that vegetation roots grow vertically, so tension is exerted to them as soil is sheared. This model is also used by De Baets et al., [55,56] where they tested root tensile strength and root distribution for selected plant species.

2.6. Mechanism of Soil-Root Reinforcement

Figure 4 shows that vegetation enhances the soil shear strength by transferring the shear stress developed in the soil to roots fibers through the tensile strength mobilized in the roots. When a tree roots extends across a shear surface, or upwards beyond the potential failure mass, making a small angle with the downslope direction of the shear zone and the roots within the shear zone develop tension. In other words, shear stresses in the soil mobilize the tensile resistance in the root fiber, which in turn provides greater strength to the soil.

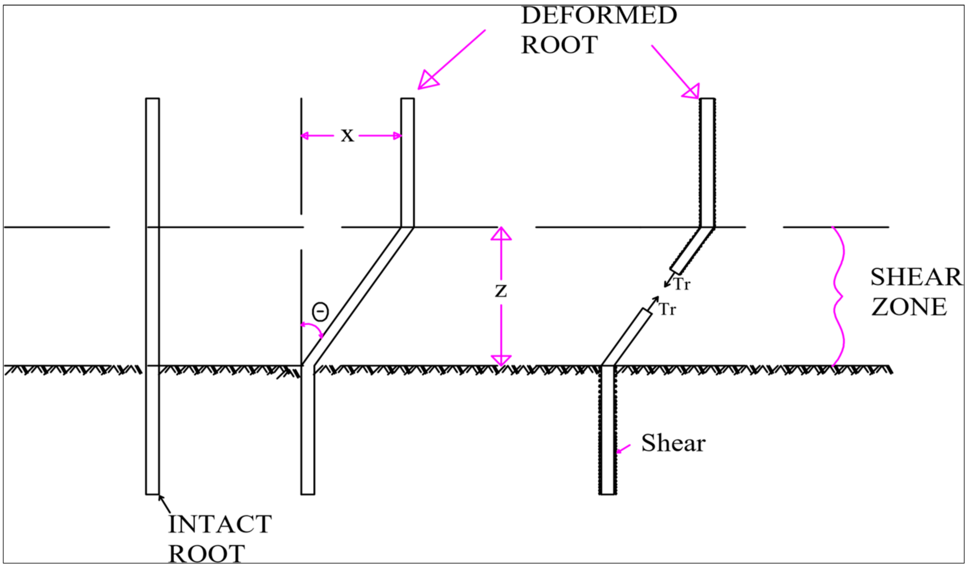

Figure 4. Interface friction between soil and root.

If the soil is rooted, the increased soil shear strength can be expressed as additional cohesion:

$$C_r = 100{\cdot}1.2\sum\nolimits_i^n T_{ri} n_i A_{ri} \frac{1}{A} \tag{4}$$

where T_{ri} is the tensile strength of an individual root (i) and ($A_{ri}|A$) is the root area ratio (RAR) or proportion of root cross-sectional area to soil cross-sectional area A. Soil cohesion due to roots (C_r, kPa) was calculated from average T_r of each species and RAR [31,35].

The influence of vegetation roots on soil shear strength can be taken as part of the cohesive strength component of the soil-root system [28,37,39,44,55,56]. For the case when the phreatic surface is at the soil surface and location of the potential shear plane for infinite slope is at a depth z below the soil surface [11], the factor of safety is the ratio of activating force to driving force is determined by Equation (5):

$$FOS = \frac{C' + \Delta C + \left(zcos^2(\alpha)\left(\gamma_{sat} - \gamma_{w)} + w_t cos\alpha\right) tan\phi'\right]}{[z\gamma_{sat} cos\alpha sin\alpha + w_t sin\alpha]} \tag{5}$$

where, C' and ϕ' are the effective soil strength parameters, ΔC is the increased cohesion due to tree roots, α is slope angle, w_t vegetation surcharge γ_{sat} is saturated unit weight, γ_w unit weight of water, z, effective root zone. To predict the slope failure threshold conditions, the soil strength parameters are estimated from the Mohr-Columb failure envelope derived from the peak values of a series of shear stress-displacement curves.

2.7. Determination of Unit Weight of Soil

Lab tests were performed to determine the in-situ density of undisturbed soil obtained by pushing or drilling a thin-walled cylinder. The test is conducted using the ASTM D 7263 standard method. The bulk density is the ratio of mass of moist soil to the volume of the soil sample. Whereas, the dry density is the ratio of the mass of dry soil to the volume of soil sample. The unit weight of soil is determined by the following procedures (1) the soil sample extruded from the cylinder using the extruder (2) representative soil specimen is cut from the extruded sample (3) the length (L), diameter (D), and mass (Mt) of the soil specimen determined and recorded (4) then the moisture content of the soil is determined (w).

2.8. Triaxial Compression Test for the Determination of Soil Parameter

This test is performed to determine the unconsolidated-undrained shear strength of unsaturated clay soil. The triaxial compresion test is conducted according to ASTM D2850 testing procedures. The unconsolidated-undrained (UU) triaxial compression test was conducted at different soil-water contents. Different confining pressures were applied to each specimen. The shear velocity was controlled at 1.27 mm/min in the test. The stress was recorded at intervals of 0.4 percent axial increment. When the peak value of deviator stress reaches the maximum, the test continued for an additional 5% axial strain. If no peak value is recorded, the test is stopped when total axial strain reached 20 percent.

From the triaxial compression tests, the fundamental slope stability analysis parameters were extracted. These are the friction angle, soil cohesion, elastic modulus (E) and Poisson's ratio (υ). These parameters are then used in computer model to predict how the material behaves in the slope stability analysis. Soil and plant root parameters for numerical modelling are summarized in Table 1 below.

Table 1. Summary of Soil and root parameters for slope stability analysis.

Soil Parameters at (16%) Moisture Content					
Saturated Unit Weight of Soil (kN/m^3)	Un Saturated Unit Weight of Soil (kN/m^3)	Poisson's Ratio	Elastic Modules of Soil (kN/m^3)	Soil fiction Angle (°)	Cohesion of Soil (kN/m^2)
18	16	0.2	3125	4	47
Root Parameters					
Plant Species	Diameter Range (mm)	Apparent Root Cohesion (kPa)		Root Tensile Strength (MPa)	Effective Root Zone (m)
Salix subserrata	0.25–6.5	9.9		41.85	2.2
Eucalyptus globules	0.26–5.8	7.44		32.18	1.8
Psidium guajava	0.74	4.27		38.47	1.6
Chrysopogon zizanioides	4.20.36–1.94	0.91		33.08	1
Pennisetum macrourum	0.25–2.1	0.84		23.13	1

2.9. Finite Element Slope Stability Analysis Method

The factor of safety was computed using the PLAXIS 8.2 Geotechnical software. The effect of plant root reinforcement on the slope material is carried out by using soil stiffness and shear strength parameters, soil moisture variation, and root parameters. The plain-strain Mohr-Columb model with 128 elements was used to mesh the soil material. All the slope boundary faces are open except for bottom of the slope which is closed (motionless). The generation of mesh is based on the triangulation procedure. Medium mesh discretization are defined for the model. Simple sketch of the slope with the geometry, dimensions, discretization and boundary conditions are shown in Figure 5. To assess the impact of plant roots to the slope stability, the factor of safety (FOS) of the slope is calculated using finite element method (PLAXIS2D) [31,57]. The calculation of the FOS for the slope in the PLAXIS 2D package is based on the strength reduction (phi-c) procedures [58,59].

Two different soil moisture content are taken at different season. Namely, soil moisture content at 16% and 23%. The study intended to investigate weather systematic change in soil moisture content along hill slope affects soil-root reinforcement. The input parameters used for modelling are Young Modulus of elasticity (E), Poisson's ratio (υ), cohesion (C'), friction angle of soil (φ'). The principal vegetation-related input parameters used in the PLAXIS model are, apparent root cohesion (C_r), effective depth of root zone (H_z) and root tensile strength (T_r). The boundary faces of 2D displacement imposed freely to move except for the bottom boundary of the slope face, which is assumed to be non-movable. In this study, the effect of the spatial distribution of vegetation on slope stability was evaluated. The FOS of the slope determined with homogenous slope (β = 45°) with a height, H, of

14 m was considered. The root cohesion, C_r, depth of root zone, H_r, and the tensile strength of the root, T_r, were variable for each plant species.

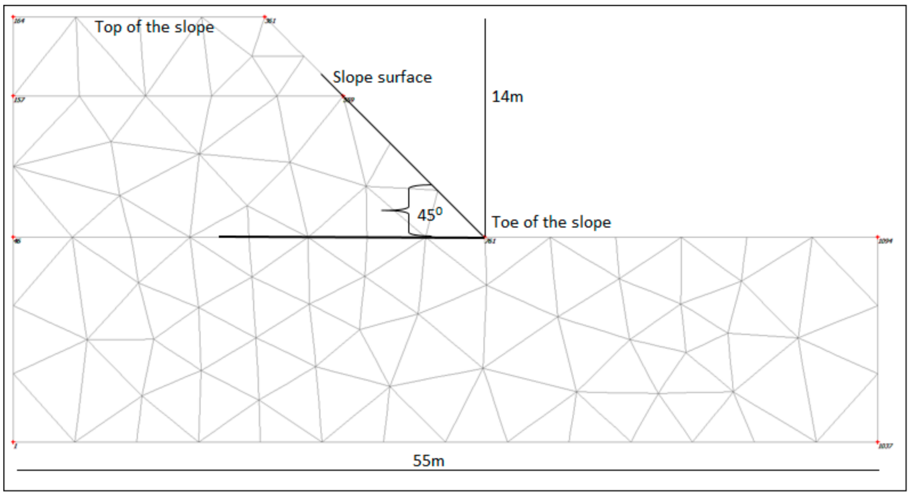

Figure 5. Schematic sketch of geometry of the slope, dimensions, discretization and boundary conditions.

The soil type in this research is cohesive clay soil, of which some soil properties, such as unit weight, cohesion, friction angle, poisons ratio, modules of elasticity and moisture content were determined from laboratory tests. The parameters for soil moisture content (ω) =16%; are: unit weight (γ) = 16 kN/m^3; Young's elastic modulus (E) = 3.125 MPa; Poison's ratio (υ) = 0.2; friction angle (ϕ) = 4°; cohesion (c) = 47 kPa; dilatancy angle = 0°; the parameters for soil moisture content (ω) = 23%; are: unit weight (γ) = 18 kN/m3; Young's elastic modulus (E) = 3.10 MPa; Poison's ratio (υ) = 0.2; friction angle (ϕ) = 3°; cohesion (c) = 50 kPa; diltancy angle = 0°. Other input parameters for the soil and plant species are given in Table 1. The cohesion of clay soil increases with increase of water contents at certain limits above which they started to decrease. In other word, cementation (cohesion) force increase with increasing water contents up to certain limit. Above which this force decreases because of excessive water content. Therefore, 23% water content is not excessive to decrease cohesion of soil.

All selected plant species were considered in the simulation at the four locations of the slope. Namely, on the entire slope, on slope surface, only at the top, and only at the toe. The results from the finite element slope stability analysis were presented as "stable slope" when the factor of safety (FOS) is greater than 1.0, and "unstable slope" when the FOS is less than 1.0. The geometry of the slope was modelled using the PLAXIS 2D interface. The slope has uniform cross-section, the corresponding stress state and loading scheme over a certain length are perpendicular to the cross-section (*z*-direction). For in-plane strain, it is assumed that the strain and displacement in the z-direction are zero but the normal stresses are different from zero.

In PLAXIS-based finite element analysis, strength reduction technique is utilized to conduct slope stability analysis by incorporating the effect of plant roots as root-soil reinforcement. The strength reduction techniques for finite element slope stability analysis have been successfully adopted by many authors [23,38,57]. This analysis method allows finding the FOS of slope by initiating a systematic reduction of shear strength parameters, Cf and φf, wich are defined in Equations (6) and (7):

$$Cf' = \frac{Cc}{SRF} \tag{6}$$

$$\varphi f' = arctan\left(\frac{tan\phi}{SRF}\right) \tag{7}$$

where, SRF is the strength reduction factor. The factor of safety (FOS) for slope stability is the value of SRF to bring the slope to failure.

3. Results and Discussion

3.1. The Effect of Spatial Distribution of Vegetation on Slope Stability

Figure 6 shows the computed factor of safety (FOS) of the slope for non-vegetated and vegetated when plants grew on entire slope surface. The result of the FOS is depended on the root penetration depth/growth depth in to the soil for all plant species. The factor of safety for the bare slope is 0.956, which indicates the slope is unstable. When the slope is vegetated the factor of safety drastically increased. For instance, when *Salix subserrata* is grown on the entire slope, the FOS increased from 0.956 to 1.284, which is the highest increase in FOS among all plant species. Plant species, *Salix subserrata* (shrub), *Eucalyptus globules (tree) and Psidium guajava* (shrub) increased the stability of the slope better than the grasses species (*Chrysopogon zizanioides and Pennisetum macrourum)* which are characterized by shallow root systems.

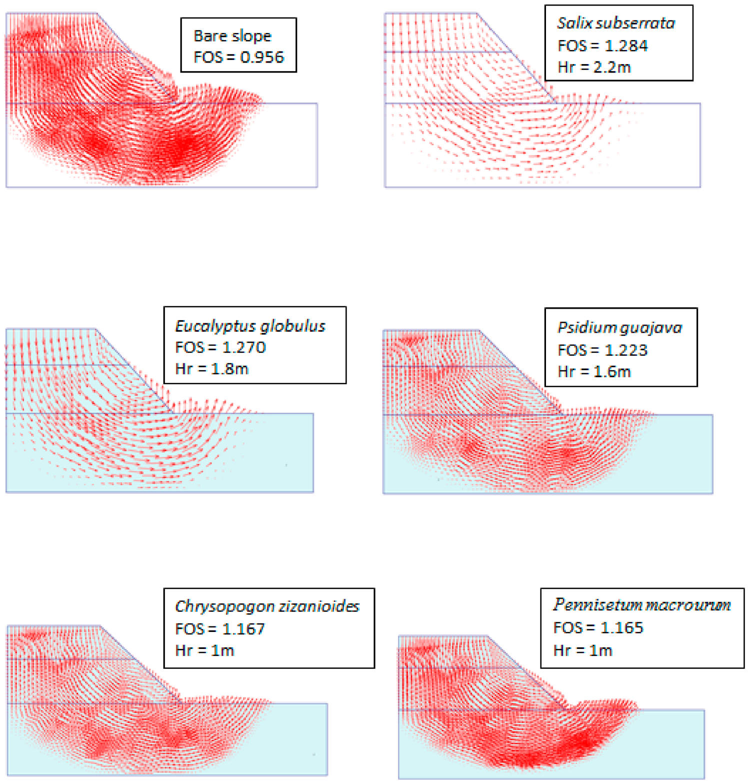

Figure 6. Factor of safety for all plant species, in the case of vegetation on entire slope surface.

The influence of spatial distribution of plants on slope factor of safety when grown on the entire slope, on the surface, on the top and at the toe of the slope are illustrated in Table 2. When the vegetation grew on the entire slope, the improvement in FOS ranged from 21.1–34.3% for all plant species. When vegetation grew on the slope surface only, the improvement of FOS ranged from 19.3–32.1%. When vegetation grew on the top of the slope, the improvement of FOS ranged from 2.4–11.5%. When the vegetation is planted on the toe of the slope the improvement in FOS is between 6.1–16.4%. The findings indicated that better slope improvement is observed when plants are vegetated on the entire slope surface.

Figures 7 and 8 shows, the shear strain of typical elements for bare/non-vegetated and vegetated slope. Reinforced slope has small shear strain as compared with unreinforced slope. Deformation concentration occurred in unreinforced slope. Deformation localization occurred for unreinforced slope mainly in upper and middle part of the slope as reveled in Figure 7. It is observed that plant root reinforced slope significantly decreases slope deformation and ensures stability.

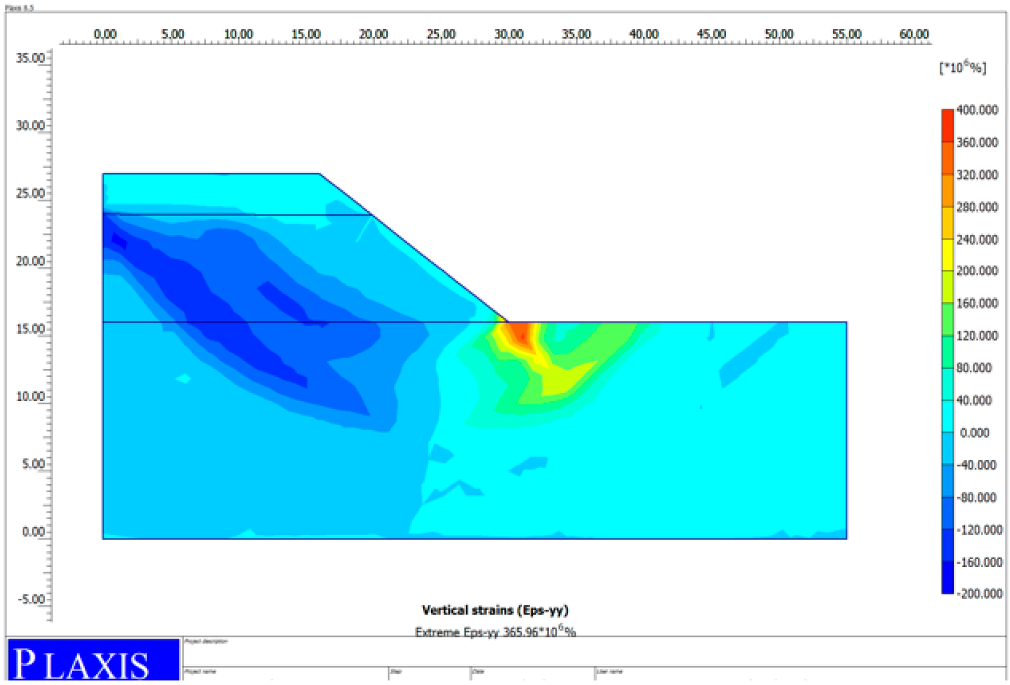

Figure 7. Strain displacement distribution of numerical analysis for non-vegetated slope.

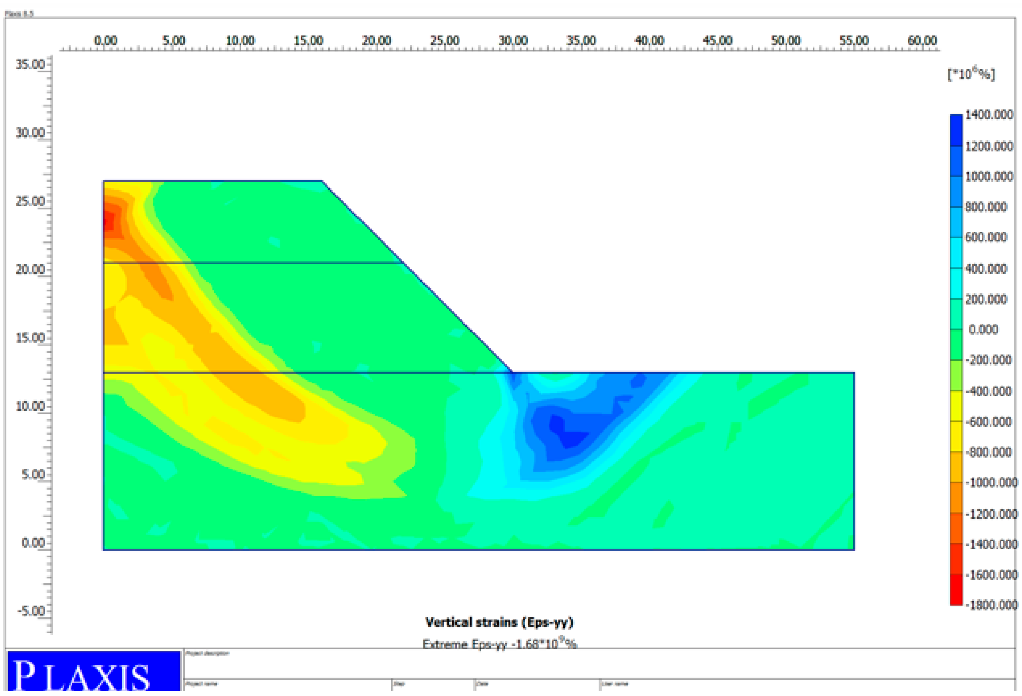

Figure 8. Strain displacement distribution of numerical analysis for non-vegetated slope (*Salix subserrata*).

Table 2. Calculated Factor of safety when Plant Species Were Simulated at Different Locations of the Slope.

Plant Species	Vegetation Scenarios							
	Entire Slope	Increment in (%)	Slope Surface	Increment in (%)	Top Slope	Increment in (%)	Toe of Slope	Increment in (%)
bare soil	0.956	-	0.956	-	0.956	-	0.956	-
Salix subserrata	1.284	34.3	1.263	32.1	1.066	11.5	1.113	16.4
Eucalyptus globules	1.270	32.8	1.245	30.2	1.057	10.6	1.103	15.4
Psidium guajava	1.223	27.9	1.198	25.3	1.023	7.0	1.065	11.4
Pennisetum macrourum	1.165	21.9	1.143	19.6	0.979	2.4	1.014	6.1
Chrysopogon zizanioides	1.167	22.1	1.140	19.3	0.984	2.9	1.015	6.2

3.2. Effect of Soil Moisture Variation on Slope Stability

The influence of soil moisture variation on the stability of the slope are presented in Table 3. The factor of safety (FOS) decreased from 0.956 to 0.884 (8.14%) for bare slope/non-vegetated slope when soil moisture content is increased from 16% to 23%. Decrease in factor of safety is also observed for vegetated slope as soil moisture increased. For instance, the value of FOS for the slope vegetated with *Salix subserrata*, decreased from 1.284 to 1.192 (7.71%). Similarly, the effect of the remaining cases of plant species shows similar trend. It is observed that decrease in FOS for all plant species under various soil moisture level. However, *Salix subserrata* shows less percentage decrement in factor of safety when compared with other plant species. This indicated that *Salix subserrata* can ensure the stability of the slope at different soil moisture variation better than other plant species.

Table 3. FOS computed by for the vegetated and bare slope with different groundwater levels.

Plant Species	When Soil Moisture Content (16%)	When Soil Moisture Content (23%)	Percent Decrement
Fallow soil	0.956	0.884	8.14
Salix subserrata	1.284	1.192	7.71
Eucalyptus globules	1.270	1.141	11.3
Psidium guajava	1.223	1.086	12.6
Pennisetum macrourum	1.165	1.025	13.7
Chrysopogon zizanioides	1.167	1.035	12.8

The results of the study shows that during the wet condition, the effect of the plant roots on FOS was smaller than dry condition. This is because, increase in soil moisture content leads to a decrease in the ϕ'' (effective friction angle of soil) and C' (effective cohesion of soil), and increase soil weight and pore water pressure in slope [9,12,13,55,60]. This result agreed with the researchers findings on the effect of soil moisture variation on slope stability, who noted that an increased in soil moisture, aggravated the activating force rather than increasing resisting force, this tends to reduce the FOS of the slope [13,61–65]. The plant species *Salix subserrata, Eucalyptus globules* and *Psidium macrourum* are promising plant species that could stabilize slope at worst case scenarios (wet conditions) as compared with grass species.

3.3. Influence of Root Penetration Depth on Factor of Safety

Table 4 shows the effect of root penetration depth on the factor of safety. The decrease in factor of safety is observed due to decrease in root density of vegetation as soil depth increased. For instance, the root cohesion values for *Salix subserrata* are 2.44 kPa and 0.17 kPa at a soil depth of 0.2 m and 2.2 m respectively. The corresponding FOS at this soil depth intervals were 1.222 and 1.108, respectively. The results confirmed that better soil root-reinforcement is achieved near the surface of the slope than deeper soil depth, because of decrease in root density as we go down to the soil depth. The grasses, *Chrysopogon zizanioides* and *Pennisetum macrourum* has weaker root cohesion as compared with *Salix subserrata*, *Eucalyptus globules* and *Psidium guajava.* These two grass species are effective in the upper soil depth of slope and not applicable for soil mass of slope more than 1 m depth. The result confirmed that the factor of safety of slope has a positive and negative relationship with apparent root cohesion (C_r) and depth of root penetration respectively as shown in Figure 9. In general, the analysis shows that the stability of the slope is more ensured at the upper soil layers and decreased gradually to the maximum length of root for all plant species.

Table 4. Computed FOS for the slope with different root penetration for all plant species.

Salix subserrata			*Eucalyptus globules*		*Psidium guajava*		*Chrysopogon zizanioides*		*Pennisetum macrourum*	
Depth (m)	**C_r (Kpa)**	**FOS**	**C_r (Kpa)**	**FOS**	**C_r (Kpa)**	**FOS**	**C_r (Kpa)**	**FOS**	**C_r (Kpa)**	**FOS**
0.2	2.44	1.222	2.06	1.203	0.91	1.169	0.3	1.134	0.32	1.152
0.4	2.2	1.219	1.49	1.187	1.08	1.175	0.18	1.13	0.21	1.149
0.6	1.53	1.187	1.09	1.176	0.59	1.161	0.18	1.13	0.14	1.147
0.8	0.77	1.165	0.73	1.165	0.67	1.165	0.15	1.13	0.1	1.146
1	0.61	1.15	0.48	1.158	0.36	1.158	0.1	1.13	0.06	1.145
1.2	0.68	1.143	0.43	1.157	0.33	1.157				
1.4	0.44	1.136	0.42	1.156	0.19	1.154				
1.6	0.41	1.125	0.39	1.156	0.13	1.151				
1.8	0.37	1.114	0.35	1.146						
2	0.28	1.11								
2.2	0.17	1.108								

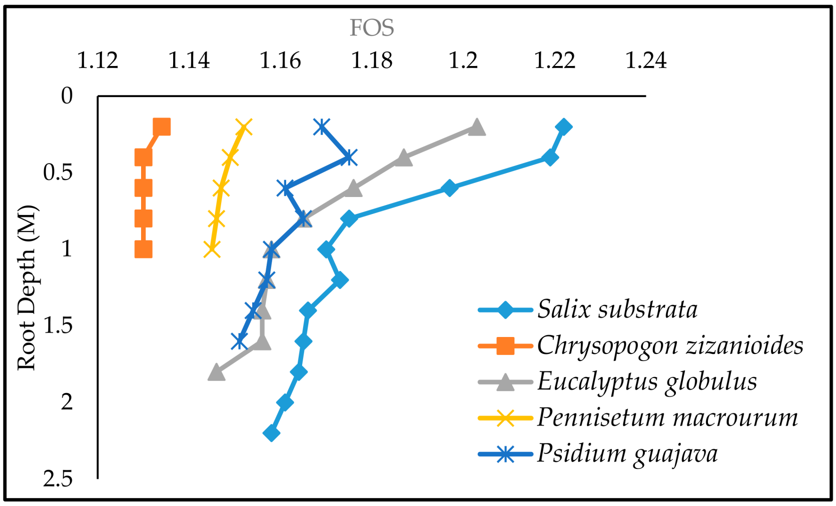

Figure 9. The factor of safety vs root depth for all plant species.

The factor of safety (FOS) is calculated by incorporating the apparent root cohesion at 0.2 m interval of soil depth for all selected plant species as shown in Table 4. The effect of additional cohesion provided by roots with different root penetration depth into the soil indicated by [1,25,59,65,66]. Figure 9 illustrated that the value of FOS decreased for individual plant species as the root penetration in to the soil increased. Similarly, the FOS decreased as the root cohesion values decreased. In general, as the root penetration depth increased, the overall roots cohesion value increased, and the better soil-root reinforcement achieved. The result implies that root matric has significant effect on cohesion and this effect varies with the depth depending on root length density. It has been reported that soil strength increases with depth due to the increase in interaction between root and soil particles [30,40,67,68]. In the present study, plants roots has greatest effect at shallow depth of slope than deeper, where the root length density is generally the highest.

In this study, plants weight and wind effect is not considered, for the following reasons: (a) since the weight of the trees is spread out over the entire slope, it has an insignificant effect on the slope failure. In addition to this, selected plant species are very short and small in weight, the plant weight rarely plays a role in slope failure. From the site investigation the maximum depth of failure plane of the study area is about 2 m. Since the root depth of the plant species is 2.2 m, it can cross the failure plane and the extra strength provided by the roots balances the weight of plants. Where the root of tree is entirely within the potential failure, the plant is likely to be small relative to the size of failure block. (b) Wind blowing is likely to affect slope stability adversely. Strong wind blowing parallel to the ground surface exert an overturning moment on plants. However, the study area is stagnant for wind blowing effect. Therefore, the effect of wind plants is insignificant in causing slope prone to failure in the study area.

Among the selected plant species, soil-root reinforcement achieved up to soil depth of 2.2 m by *Salix subserrata*. This plant species reveals the highest root reinforcement with significant increase in the cohesion with respect to soil depth. It has the highest percentage increase of root reinforcement at all soil depth when compare with other plant species (Table 4). The results imply that the high capacity of root reinforcement this plant species ranks it as an outstanding slope plant.

3.4. Effect of Vegetation Spacing to Safety Factor of Slope

To observe the influence of vegetation spacing on the stability of the slope, squared spatial distribution pattern for slope plantation have been chosen as depicted in Figure 10. The pattern is arranged using inter-tree distance along the slope and opposite to the slope direction through the entire slope surface.

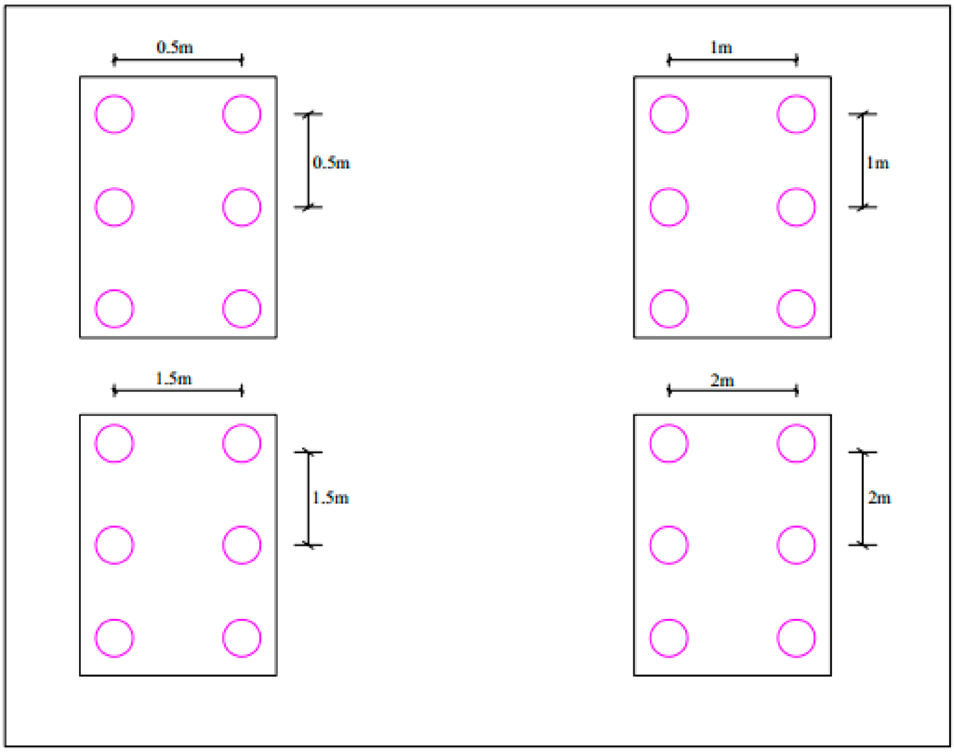

Figure 10. Square distribution pattern of plant species within stand in corridor.

The influence of vegetation spacing on the stability of slope is shown in Table 5. The experiment was done using four different spacings, 0.5 m, 1 m, and 1.5 m and 2 m, on the entire slope. The FOS of the slope with smaller vegetation spacing considerably enhanced stability of the slope than highly spaced vegetated slope (Figure 11). For instance, slope vegetated with *Salix subseratta*, with tree spacing of 0.5 m, 1 m, and 1.5 m and 2 m, the FOS is 34.3%, 30.07%, 30.07% and 29.5% respectively, greater than that of bare slope.

Table 5. Computed FOS for the slope with different vegetation spacing on the entire slope.

Plant Species	Vegetation Spacing							
	0.5 m	Increment in (%)	1 m	Increment in (%)	1.5 m	Increment in (%)	2 m	Increment in (%)
bare soil	0.956	-	0.961	-	0.961	-	0.961	-
Salix subserrata	1.284	34.3	1.250	30.07	1.250	30.07	1.245	29.5
Eucalyptus globules	1.270	32.8	1.185	23.3	1.179	22.7	1.171	21.8
Psidium guajava	1.223	27.9	1.098	14.3	1.092	13.6	1.086	13
Pennisetummacrourum	1.165	21.9	1.004	4.5	0.987	2.7	0.983	2.3
Chrysopogon zizanioides	1.167	22.1	1.009	4.9	0.985	2.5	0.985	2.5

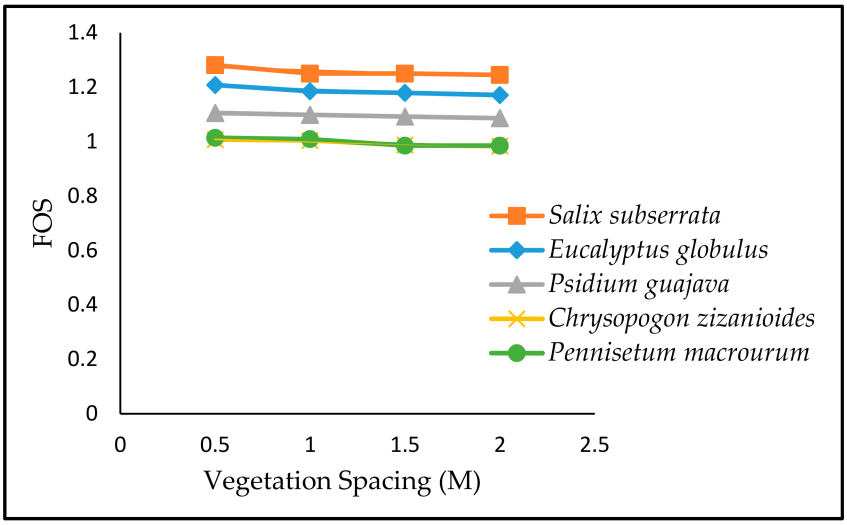

Figure 11. The factor of safety vs vegetation spacing for all plant species.

The safety factor of the vegetated slope increases with decreasing vegetation spacing. Plants vegetated on entire slope surface with smaller vegetation spacing increase root density and enhanced interlink of thin roots for soil reinforcement as depicted by [2,12,33,40,69]. The result from the analysis shows that as the spacing of vegetation increases, enhancement of soil shear strength of the slope decrease and the slope is prone to failure. It was observed that slope with narrow spaced vegetation, the depth failure plane increased, in contrarily, as the spacing of vegetation increased, the depth of failure plane become shallower.

3.5. The Effect of a Change in Slope Angle on Slope Stability

The effects of different slope angle on FOS for bare slope and vegetated slope was shown in Table 6.

Table 6. Comparison of the factor of safety of slope for varies slope angle.

Plant Species	The Factor of Safety, FOS				
	Slope Angle 45°	Slope Angle 30°	Slope Angle 20°	Slope Angle 15°	% Increase
Fallow soil	0.956	0.987	1.102	1.128	17.99
Salix subserrata	1.284	1.351	1.418	1.489	15.96
Eucalyptus globules	1.270	1.331	1.397	1.467	15.50
Psidium guajava	1.223	1.284	1.348	1.416	15.78
Pennisetummacrourum	1.165	1.223	1.284	1.348	15.70
Chrysopogon zizanioides	1.167	1.225	1.287	1.351	15.70

An increase in FOS is observed for both vegetated and non-vegetated slope as the slope angle reduced. For instance, the calculated FOS with slope angle of 45°, 30°, 20°, and 15° when vegetated with *Salix subserrata* were 1.284, 1.351, 1.418, and 1.489, respectively. A similar trend is observed as the slope angle decreased the FOS for all plant species increased. Generally, the flatter the slope the better stable than the steeper slope.

It can be observed from Figure 12, for all slope angles, the FOS increased as the slope angle decreased. When the slope angle reduced from 45° to 30°, little improvement of FOS is observed for the bare slope, which is lower than 1, implying very unstable or failed. However, as the slope angle changed to 20° and 15° the critical stability was observed with marginal value greater than one. This improvement confirmed that the analyzed slope would be theoretically stable at slope angle less than 30° and unstable at slope angle greater than 30°. It is observed that the modification of slope is more effective when the slope is vegetated with *Salix subserrata* than other plant species. In general, these results suggested that the slope angle reduction, and slope vegetation is a useful method of slope stabilization.

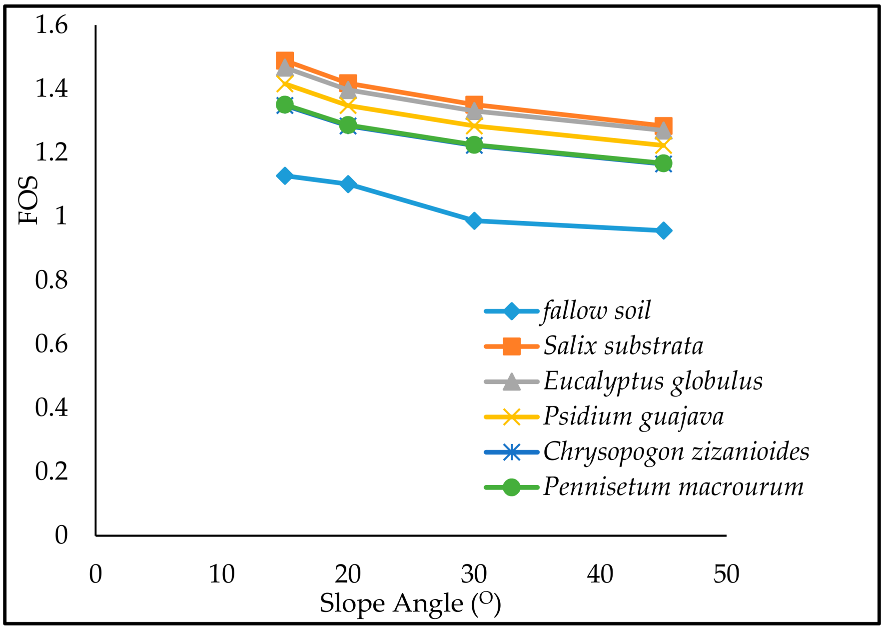

Figure 12. Values of the factor of safety for various plant species at different slope angle.

The result of the analysis shows that as the slope becomes steeper the factor of safety reduces. This is because a steeper slope has a higher driving force than a flatter slope and this force reduces the factor of safety. The smaller slope angle is more stable than the sharp slope, as suggested by [31,52]. The findings from Figure 10 show a negative relationship between the factor of safety and slope angle. The slope angle have the most significant influence on the stability of the slope [52]. This study acknowledged that the slope angle is a determinant factor for the stability of the slope, slope with a high inclination angle is more susceptible to slope instability.

4. Conclusions

The findings of the study can be summarized as follows: for the same slope geometric configurations, the slope that was initially unstable without plant roots reinforcement became safe when reinforced by plant roots. Plant roots have a significant role in stabilizing shallow failure of the slope along road cut slopes. Generally, the stability of the slope has increased as the value of root cohesion and effective depth of root zone increased. In addition, the result showed that better FOS was obtained for slope with vegetation covered on entire slope surface than with plant-covered on the top, on the surface, and toe of the slope. The failure mechanism of the study area was initiated at a maximum depth of 2 m. As the depth of root penetration increased on the entire ground surface, the safety factor increased. Among studied plant species, the root of *Salix subserrata* can penetrate beyond the failure zone and produced a higher factor of safety and can reinforce soil up to the depth of 2.2 m.

The slope of the study area was more susceptible to failure for increased soil moisture content and this leads to a decrease in the factor of safety. On the contrary, as the soil moisture content decreases the factor of safety increases. This is because, as the water contacts with soil, the shear strength of soil declines. In general, the wet condition of the slope combined with steeper slope is the most critical situation for slope failure along road corridors. The analysis shows that roots distributed with smaller vegetation spacing, throughout the slope surface have a positive effect on slope stability, with a significant increment of the FOS. From PLAXIS 2D modelling the actual slope of the study area is unstable. Generally, decreasing in slope cut inclination along slope of mountainous area in combination with plant vegetation and providing gabion at the toe of the slope enhances slope stabilization along transportation corridors. Because, the stability is achieved by self-weight of gabion. In addition, gabion is advantage in filtering excess pore water developed in the slope. In conclusion, among the five-studied plant species, *Salix subserrata* is the most promising in slope stabilization due to its better root density and mechanical characteristics.

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