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Role of Acacia Tree Root's Reinforcement in Hill Slope Stability

U. D. Patil[1], M. Yeo[2], E. Aquino[3], S. S. C. Congress[4], and E. Demeulenaere[5]

[1]*Associate Professor, University of Guam, Mangilao, Guam, USA, email: patilu@triton.uog.edu*

[2]*Assistant Professor, University of Guam, Mangilao, Guam, USA, email: yeom@triton.uog.edu*

[3]*Research Assistant, University of Guam, Mangilao, Guam, USA, email: aquinoe10849@gotritons.uog.edu*

[4]*Assistant Professor, North Dakota State University, Fargo, North Dakota, USA, email: surya.congress@ndsu.edu*

[5]*Associate Director, Centre for Island Sustainability, University of Guam, Mangilao, Guam, USA, email: else@uog.edu*

ABSTRACT

Bio-engineering techniques such as planting trees/grass along hill slopes to prevent rainfall-induced slope failures is gaining worldwide acceptance. Such environment-friendly and cost-effective techniques can be an alternative slope stabilization solution in remote and rural hilly regions. Non-native, Acacia Auriculiformis tree have been recently used to re-vegetate barren scars in savanna grasslands in Guam with the aim to restore its degraded ecosystem. In this study, laboratory and field studies combined with finite-element-based transient seepage, and a simple infinite slope stability example were performed to quantify the role of Acacia tree roots in improving the stability of the shallow surface of hill slopes in southern Guam. Root samples from various depths were collected and tested for their tensile strength and root morphological characteristics, namely root area ratio (RAR). A power-fit relationship was obtained between root diameter and tensile strength offered by the Acacia roots. The offered root tensile strength ranged between 10-173 MPa and it increased with decreasing root diameter. Root bundle theory was used to translate the tensile strength offered by the roots into additional shear strength to predict the root-enhanced mechanical shear strength within the soil-root matrix. Results show that the factor of safety (FOS) increased many folds due to the inclusion of root fibers in the soil matrix as compared to the barren hill slope. Acacia roots provided a decent amount of stability through an increase in the factor of safety via root reinforcement during extreme precipitation events, which are common to the Island of Guam.

Keywords: bioengineering, rainfall-induced slope failures, root tensile strength, root area ratio, root reinforcement, soil water retention curve

1 INTRODUCTION

Recently, there has been a frequent occurrence of extreme rainfall events such as the ones resulting in high intensity rainfall in short duration. This has resulted in numerous rainfall-induced slope failures on the Island of Guam and several others in western pacific (Patil et al., 2022). Conventional soil stabilization methods include adding cementitious additives such as cement, lime, fly ash, and blast furnace slag that undergo pozzolanic reactions with soil particles thereby improving the shear strength of weak soil. Mechanical methods include adequate compaction and chemical stabilizers can also be added that can alter the chemical composition and improve the physical properties of weak soil. However, these techniques leave carbon footprint and hence not eco-friendly. On the contrary, the use of vegetation in maintaining stable slope is gaining support and interest from engineering community due to its application being more cost effective, aesthetic in appearance and environment friendly.

Rain intensity, hydraulic conductivity, soil water retention curve (SWRC) properties, and geometry of slope play a key role among other factors that control the rainwater permeation into slope (Patil et al., 2022; Cecconi et al., 2015). Rainwater infiltrates slope and increases its water content if the hydraulic conductivity of soil is greater than the rain intensity. On the other hand, rain results in runoff if vice-versa condition exists. A slope made from low hydraulic conductivity soil, like the one used in this study would delay the water infiltration increasing degree of saturation of only few feet of top layer. This coupled with continuous rainfall could trigger the rainfall induced slope failure by increasing the pore water pressure and reducing the effective stress in the already saturated soil matrix.

Bioengineering techniques such as planting vegetation provides stabilization to a slope through hydrological and mechanical beneficial effect provided by their roots (Patil et al., 2022; Badhon, 2021; Cecconi et al., 2015). Rahardjo et al (2018) conducted slope stability analysis with and without Caesalpinia Crista roots during and after rainfall. Their studies revealed increasing shear strength and reduction in infiltration into the slope due to presence of *Caesalpinia Crista* roots. Recently, Li et al. (2021) conducted numerical analysis and field measurements demonstrating effectiveness of both Vetiver grass and capillary system in improving stability of residual slopes during rainfall event. Similarly, numerical analysis conducted by Satyanaga and Rahardjo (2019) showed that introduction of *Melastoma Malabathricumas* as a vegetative cover minimized the rainfall infiltration, and its roots improved the factor of safety of slopes made from old alluvium soil. Roots tend to form a web of network within the soil, which helps to prevent the dislodge of surficial soil particles under erosive forces such as wind and rainwater. They also tend to grow deep in search of water and nutrients that are essential for their growth. As the roots extract water from surrounding soil, it puts soil under tension and reduces its water content. This hydraulic effect imposed by the network of roots increases the apparent cohesion due to suction being induced in soil-root zone matrix. Ultimately, this improves the shear strength of soil (Patil et al., 2022; Patil et al., 2021; Cecconi et al., 2015). Similarly, the root network acts like reinforcement to soil, which is weak in tension. The root tensile strength offered by roots additionally increases the shear resistance offered by soil to the sliding mass of soil along slopes. The tensile strength offered by the roots depend upon root morphological characteristics such as root area ratio and chemical composition of root. This tensile strength is then translated using mathematical equations to indirectly compute the additional root cohesion. However, the pattern of root network and their root morphological characteristics differs from plant to plant. Thus, it becomes important to conduct plant and site-specific study.

The exact quantification of the root reinforcement provided by the Acacia tree on the Island of Guam has not been investigated. The main focus of this study is to find potential application of Acacia Ariculformis plant in improving stability of hill slopes in Guam. Hence, this paper documents mechanical (i.e., root tensile strength) and morphological characteristics (i.e., root area ratio (RAR)) from lab testing of a nursery grown 2-year-old Acacia Auriculiformis plant and geotechnical and hydrological properties of soil collected from hill slope from southern Guam. The unsaturated properties of stratum along test slope were assumed to be governed by Fredlund and Xing's, (1994) SWRC model. Similarly, the flow of water through stratum was assumed to be governed by Fredlund, Xing and Huang (1994) unsaturated permeability model. Finally, the mechanical effect of root reinforcement was considered in a simple infinite slope stability problem to demonstrate the beneficial role of Acacia Auruculiformis roots in improving factor of safety (FOS) of hill slopes in Guam.

2 SATURATED AND UNSATURATED PROPERTIES OF SLOPE SOIL

A case study was conducted on a 1:1 slope ($\beta = 45°$) made from relatively low hydraulic conductivity clay (CH) permeated with Acacia tree roots. Soil samples were collected from Ija watershed in Southern Guam to perform saturated and unsaturated soil testing (Patil et al., 2022). The soil water retention curve (SWRC) and its parameters along with saturated permeability and shear strength properties are mentioned in inserted caption of Fig. 1.

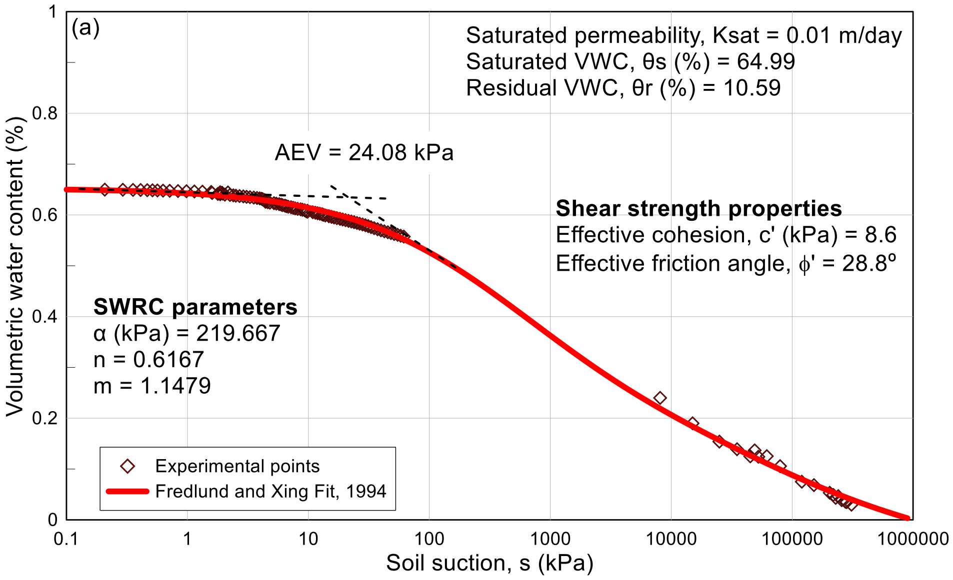

Figure 1. *Soil water retention curve (SWRC) and unsaturated soil properties of clay slope*

3 ACACIA AURICULIFORMIS ROOT MORPHOLOGICAL CHARACTERISTICS

Acacia Auriculiformis tree are draught resistant and need not be watered periodically. Hence, planting Acacia tree could be a good choice for watershed restoration, especially along remote and hilly slopes of southern Guam (Fig. 2a). Acacia root can grow deeper in search of water and the tree grows at a fast rate. Although, non-native, it has been widely used for watershed restoration in Guam, which is chief motivation for this research study.

A 2-year-old Acacia tree grown in native soil was selected from nursery for this study. It had a root depth of 0.5m. Hence, the depth of soil-root zone of 0.5m was considered in analysis. The Acacia tree was uprooted carefully and washed as shown in Fig 2b. Each root diameter was measured using a digital calliper of 0.01 mm least count. Furthermore, the root area ratio (RAR), which is one of the important morphological characteristics of roots was determined using equation: RAR = $(A_r/A_s) \times 100$, where A_r = sum of the root cross sectional area at given depth and A_s = soil sample plan area. RAR reflects the root biomass concentration and was computed at a regular interval of 5 cm below ground surface as illustrated in Fig 3. Clearly, the RAR was maximum near the ground surface and decreased non-linearly with increasing depth.

Figure 2. *Acacia trees grown in forest in southern Guam (left). Acacia Auriculiformis root system (right)*

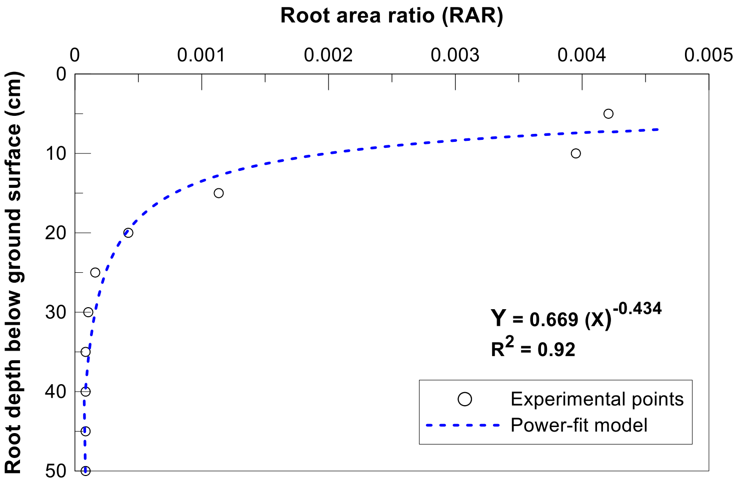

Figure 3. *Distribution of root area ratio with respect to depth*

Roots of different diameter (d_{root}) were selected and cut to a length of 6cm and tested using a Universal testing Machine. Tape was used to allow proper grip to the roots in the jaws of testing machine. Each root was then applied a tensile pull at a rate of 10mm/min and the maximum tensile force (F_{max}) required to break the root was recorded. The tensile strength (tr) offered by the root at breakage was determined using equation: $t_r = F_{max}/(\pi/4)d_{root}^2$. The maximum tensile strength (t_r) offered by the Acacia roots were plotted against their root diameters as shown in Fig 4. It was observed that the tensile strength offered by the Acacia roots decreased non-linearly with increasing root diameter (d_{root}).

The relationship between d_{root}-t_r was best-fitted with a power-fit equation with a decent correlation (R^2 = 0.71). The minimum and maximum values of root diameter and tensile strength were 0.01-2.1mm and 14.6-91.94 MPa (N/mm²), respectively.

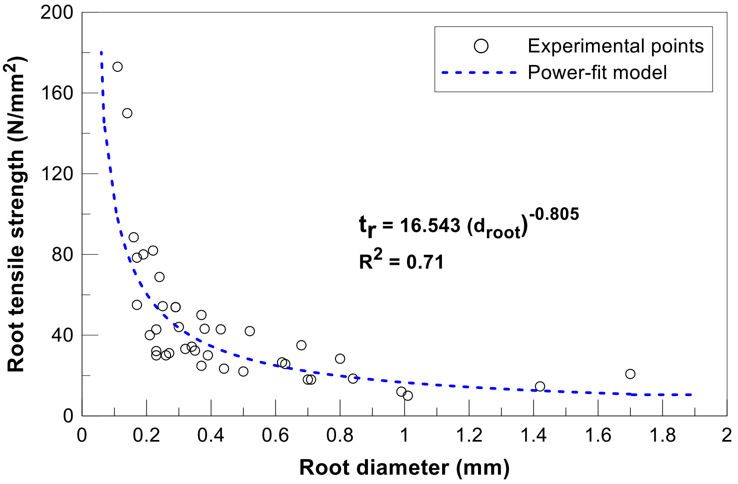

Figure 4. *Root tensile strength versus root diameter for Acacia roots*

4 ESTIMATION OF ROOT COHESION

Root cohesion was indirectly estimated using a simple model proposed by Wu et al. (1979), which considers tensile strength (t_r) and root area ratio (RAR) data. It was assumed that during sliding of soil-root mass, the roots will go into tension and offer the root tensile strength. The additional cohesion (c_r) was indirectly computed using Eq. 1 (Wu et al., 1979)

$$c_r = t_r \frac{A_r}{A_s}(sin\theta + cos\theta tan\emptyset) \tag{1}$$

Where θ is the angle of shear distortion in the shear zone, ϕ is the soil friction angle (°) and t_r is the mobilized tensile strength offered by roots. The term (sinθ + cosθtanϕ) takes into account the shear distortion, and θ value is taken as 45°. Fig. 5 illustrates that the value of c_r decreases with increasing depth. The computed c_r value corresponding to each 5cm depth below ground surface was considered in further analysis.

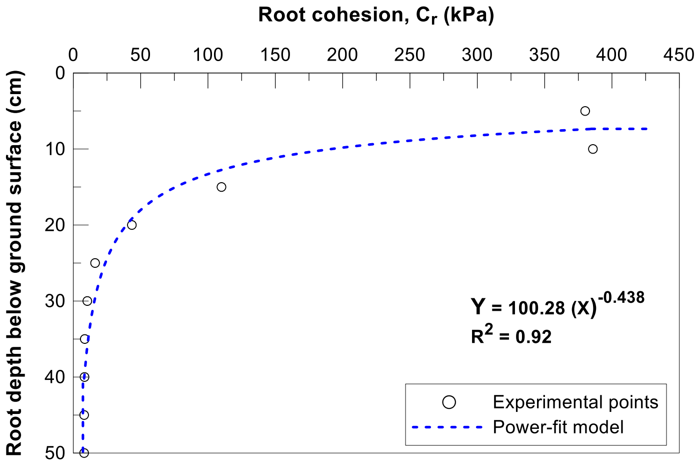

Figure 5. *Root cohesion as a function of depth for Acacia roots*

5 TRANSIENT SEEPAGE NUMERICAL ANALYSIS AND APPLIED CLIMATE BOUNDARY DATA

Numerical analysis was carried out using the finite element code by SEEP/W (GeoStudio, 2012 and 2017) to simulate the transient seepage along the idealized hill slope under a month rainfall data. Climate data was gathered from an on-site installed weather station including rainfall, relative humidity, wind speed, solar radiation, and air temperature collected at 5-minute interval for the month of October 2021, which was also the wettest month of 2021 in southern Guam. Other vegetation data such as variation of leaf area index versus time; plant limiting factor versus matric suction; root depth vs time, normalized root density versus normalized root depth, and soil cover fraction versus leaf area index were obtained from Patil et al. (2022). Two cases were considered, i.e., case a: rainfall applied on bare slope and case (b) rainfall applied on vegetated (i.e., Acacia) slope (Figs. 6-9).

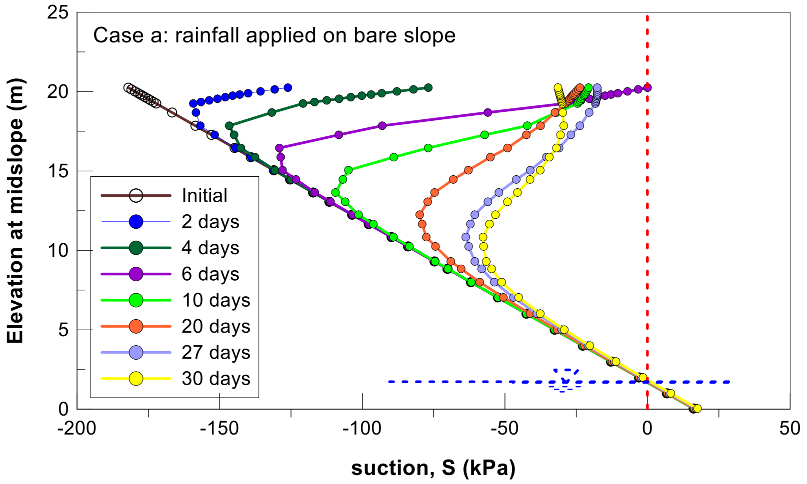

Figure 6. *Suction with respect to depth for case a*

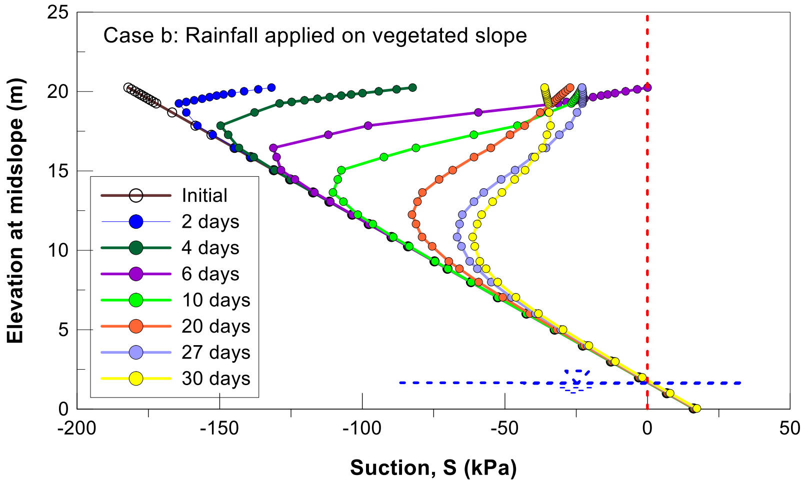

Figure 7. *Suction with respect to depth for case b*

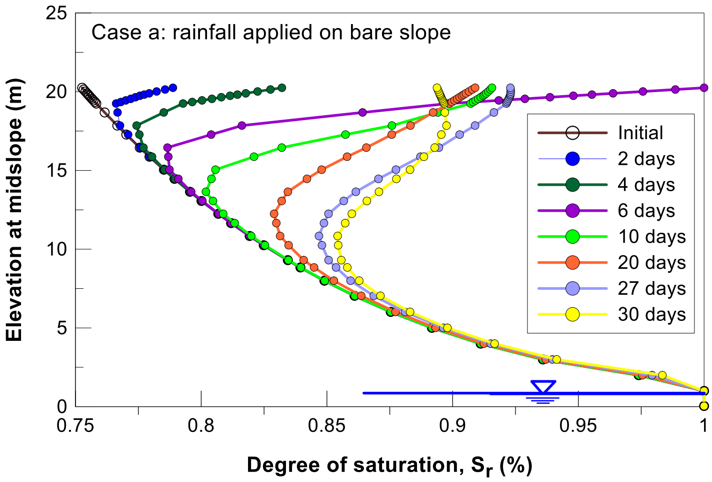

Figure 8. *Degree of saturation with respect to depth for case a*

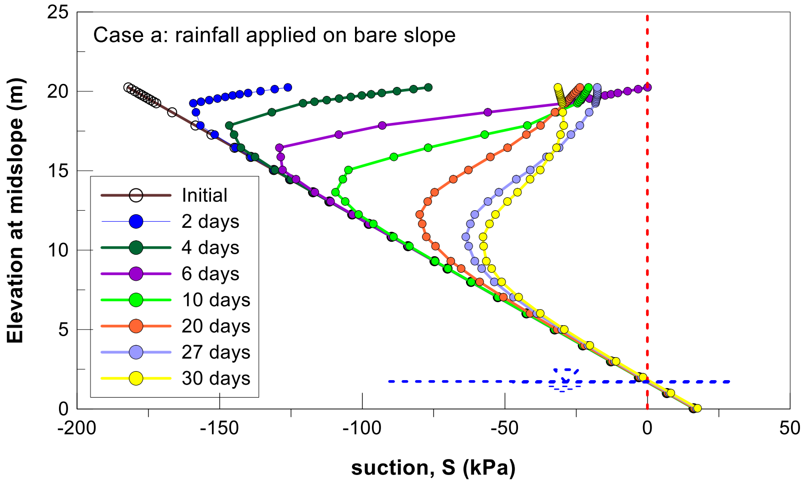

Figure 9. *Degree of saturation with respect to depth for case b*

The results of the 2-D transient seepage numerical analysis from SEEP/W were then used to create the profiles of degree of saturation (Sr), and soil suction (s) with respect to depth as shown in Figs. 6-9 along the idealized hill slope as discussed previously. The water flow and root water uptake (RWU) were simulated in SEEP/W using modified Richard's equation and Feddes et al. (1976) and Prasad (1988), respectively. Clearly, in both the case a and b the suction value approached zero value and the degree of saturation value approached one on the 6th day. Hence, 6th day results of Sr and s were used in further analysis.

6 SIMPLE INFINITE SLOPE STABILITY PROBLEM

A simple case study is presented to demonstrate the positive effect of root cohesion. The S_r and s profile from 6th day analysis were imported into a simple infinite slope stability problem using equation 2 (Vanapalli et al., 1996; Cecconi et al., 2015) to compute factor of safety (FOS) with respect to depth.

$$FOS\ (z) = \left[1 + \frac{S_r(z)\ s(z)}{\gamma\ z\ cos^2\ \alpha}\right] \frac{tan\emptyset'}{tan\alpha} + \frac{c' + c_r(z)}{\gamma\ z\ cos\alpha\ sin\alpha} \tag{2}$$

For this problem, three case scenarios were considered. First was rainfall applied on bare slope, second was vegetated slope with applied rainfall considering only root water uptake (RWU), while third case was similar to second case but including increase in shear strength from root cohesion. Figure 10 illustrates the non-linear variation of FOS with respect to depth. Clearly, the FOS was maximum near surface and decreased with increasing depth. Three case scenarios were presented in Fig. 10.

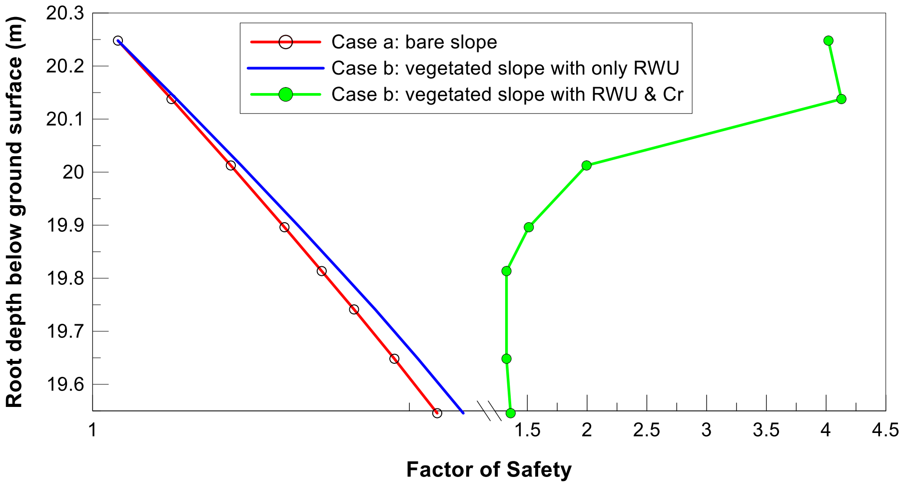

Figure 10. *Factor of safety from infinite slope stability analysis verses depth on 6th day*

First case (a) was by including rainfall but no vegetation (i.e., bare slope), which is the worst-case scenario. Second case (b) was considering rainfall and RWU by vegetation but ignoring the root reinforcement effect (i.e., root cohesion). The third case was like case second but considering root cohesion. Thus, both RWU (hydrological benefit) and root cohesion (i.e., mechanical reinforcement benefit) were considered in third case. It was observed that RWU is beneficial in improving FOS slightly at deeper depths but becomes insignificant (i.e., almost 1) at shallow and surficial depths. This is attributed to the S_r becoming 1 i.e., soil becoming saturated and suction dropping to zero at shallow depths from rain infiltration. On the other hand, the FOS increased many folds at shallow depths due to consideration of root cohesion illustrating the potential of roots in preventing shallow slope failures. Thus, in event of saturation, the RWU will cease, and slope will behave similar to bare slope. At this point the slope will try to slide which will activate the root cohesion that improves the FOS and improve slope stability at shallow depths.

7 CONCLUSION

This paper presents a simple infinite slope stability problem to demonstrate the positive benefit of root reinforcement provided by Acacia Auriculiformis plant in improving shallow slope stability. The tensile strength of Acacia root varies between 10-173 MPa and the root diameter vary between 0.01-2.1mm. The relationship between root diameter and tensile strength of roots was best fitted with a power equation. In general, the tensile strength of roots increased with decrease in root diameter. The tensile strength of roots was translated into an equivalent root cohesion (c_r) and it was computed for different root depths. Appropriate climate and vegetation boundary conditions were applied on an idealized hill slope and a transient seepage numerical analysis was performed to generate S_r and s profiles with respect to depth. Finally, the computed values of S_r, s, and C_r values at different depths were incorporated into a simple infinite slope stability equation to compute the FOS. Results show that the root cohesion plays a dominant role in improving the stability of infinite slopes at shallow depths, which illustrates the potential of Acacia Auriculiformis plant in restoration of watersheds with hill slopes in southern Guam.

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