Analyzing the influence of mechanical root properties of commonly planted agroforestry trees on Mt. Elgon. A suitability assessment of the best eco-engineering tree species for shallow seated landslide control

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Abstract

Landslides continue to occur in the Elgon region despite interventions such as tree planting initiatives aimed at restraining them. The current study assessed the mechanical properties of six selected agroforestry tree roots on slope stability with a keen focus on root tensile strength, soil shear strength, and index of root binding. A standard deviation ellipse method was applied to model the spatial distribution patterns of selected agroforestry trees. Tree-landslide relationship was tested using the Pearson correlation method while root tensile and soil shear strength with a one-way (ANOVA) and descriptive statistics respectively. Species distribution results indicate a high dispersion rate of *Croton macrostachyus* and *Markhamia lutea* across the study area and high concentration of *Albizia coriaria* downstream. A weak negative correlation ($r = -0.20 < 0.01$) was reported between diameter at breast height and landslide size. Tensile strength results observed a significant difference among species with ($F (5, 573) = [18.161]$, $p < 0.001$) and *Grevillea robusta* ($3.02 \pm 1.217 kg/mm^2$), *Albizia coriaria* ($2.53 \pm 1.382 kg/mm^2$), and *Markhamia lutea* ($2.28 \pm 1.01 kg/mm^2$) as the best performers. The best shearing species was *Albizia coriaria* with average shear strength (52.46 ± 10.24) kpa followed by *Markhamia lutea (50.70 ± 15.47)* kpa. The *Eucalyptus spp.* on the other hand underperformed with average shear strength of (46.75 ± 12.92) kpa. In conclusion, the presence of trees reduces landslide risk in an area and DBH is a very important guiding factor. *Grevillea robusta, Albizia coriaria,* and *Markhamia lutea* emerged as best performers in terms of root tensile strength and soil shear strength hence their suitability for enhancing slope stability. However, *Eucalyptus Spp*., which is widely favoured in the region for its rapid growth was the worst performer with very low shear strength. Therefore, careful consideration of the tree characteristics is essential during promotion campaigns for slope stability in fragile environments.

Key words

Landslide, tensile strength, shear strength, agroforestry, Mt Elgon

1. Introduction

Landslides are a global hazard that lead to dramatic loss of human life, property and soils every year (Chang et al., 2020; Tardío et al., 2016). According to Kavzoglu et al., (2015) landslides are responsible for 17% global fatalities. Landslide occurrence has been projected to increase due to effects of climate change and land use change (Tardío et al., 2016). In Africa, landslide have been responsible for deaths (3,171 persons), injuries (442 persons) and affected 221,907 persons between 1910 to 2020 (Thongley and Vansarochana, 2021). This has been specifically reported in countries like Burundi, Kenya, DR. Congo, Tanzania, South Africa, Uganda and Morocco (Nakileza and Nedala, 2020; El Jazouli et al., 2020). While in East Africa 14 million people have been affected by landslides and floods combined between 1971 and 2015 (Bahal'Okwibale, 2018).

These enormous impacts have stirred immense studies on landslide causal factors and solutions amongst which include application of trees to restrain landslide risk (Aghda and Razifard, 2017). This idea is known as eco-engineering method (Tardío et al., 2016). By definition, Eco-engineering is the planting of trees with good soil stability traits or characteristics that restrain landslides. This was first introduced in 1930s (Mulyono et al., 2018) to stabilize slopes prone to landslides and soil erosion in mountainous areas like Elgon. To date, eco-engineering method has proven its worth as a hydraulic channel, ground movement barrier and hydraulic pump (Hairiah et al., 2020; Balzano et al., 2019; Ghestem et al., 2011). As such, numerous tree planting initiatives have been triggered by the local communities, Non-Governmental Organizations (NGOs) and government agencies in Mt Elgon region to curtail the problem. For instance, the Face Foundation (UWA-FACE Project) in 1993 (Snoep, 2011; Lang & Byakola, 2006), the Mt. Elgon Conservation and Development project (MECDP) in 2003 (Snoep, 2011), and Trees for Global Benefit (TGB) (Masiga et al., 2012) among others.

However, landslides continue to occur even in some of the restored areas (Nakileza & Nedala, 2020). This raises debate on whether tree planting is still an effective method for preventing slope failure. Overall, there is scanty research conducted on the influence of agroforestry tree types particularly soil root reinforcement on slope stability enhancement and landslide control (Spiekermann et al., 2021; Hairiah et al., 2020). Existing studies have addressed links of landslides to biodiversity and also recognized the importance of trees on increasing soil shear strength through tensile force provided by plant roots thus reducing landslide risk on scars (Nakileza &

Tushabe, 2018; Nakileza et al., 2017). Mugagga et al., (2012) on the other hand assessed the role of land use change on landslide occurrence and found that the exponential conversion of forest land to agriculture greatly contributed to the current landslides. Recently (Graham et al., 2021) noted that agroforestry could improve community adaptation to climate change. But no specific study has been conducted to test the mechanical root properties of common agroforestry tree species in the region.

The current study therefore sought to address this information gap by analysing the mechanical role of six selected agroforestry tree species on slope stability with a keen focus on root characteristics such as the tensile strength, index of root binding and soil shear strength. The purpose of the study was to contribute towards development of an Effective Landslide Eco-engineering Mitigation and Resilience Plan (ELEMRP) through availing vital plant information for landslide risk reduction. The objectives were to analyse spatial distribution and characteristics of selected agroforestry tree species with potential to reduce slope failure in high landslide susceptible zones; and to determine root reinforcement characteristics as a feature for promoting adoption by farmers and resource managers.

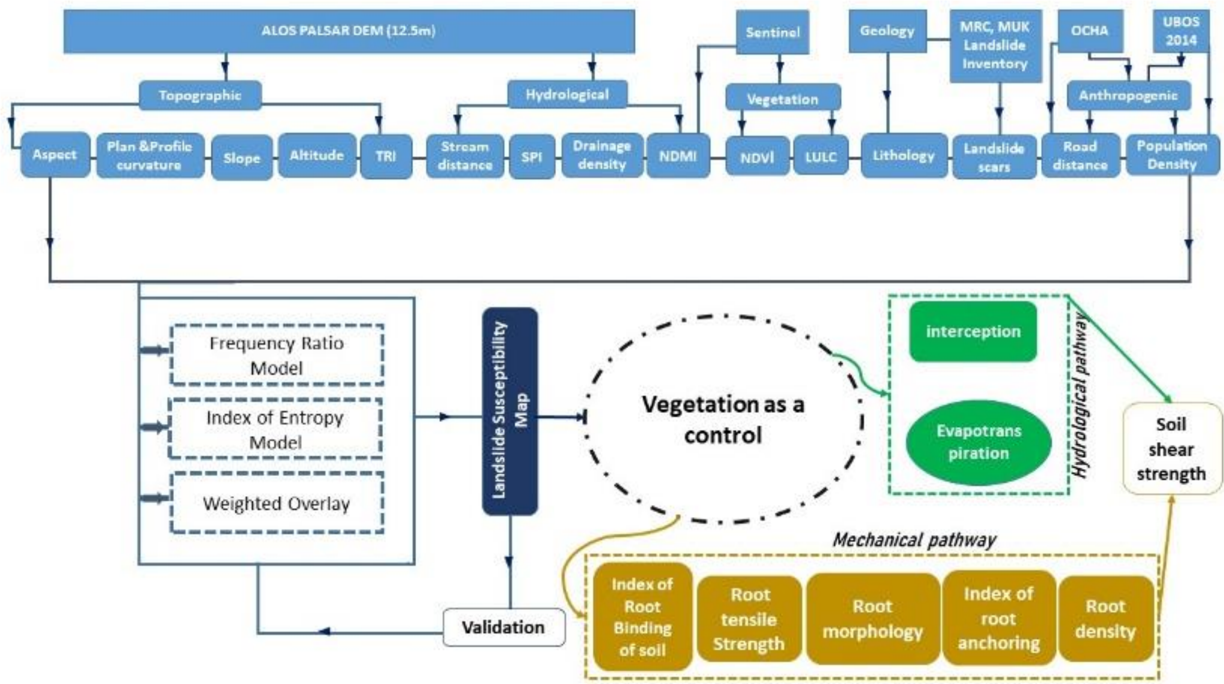
This study avails vital plant information for government and non-government agencies, environmentalists and researchers on plant root systems that support tree species selection and adoption for slope stabilization in high landslide susceptible zones. Specifically, the results provide baseline information for developing tree planting policies and plans for landslide disaster risk reduction. The findings also will guide in resource allocation especially during tree campaigns to avoid resource wastage as a result of planting wrong trees in a right place and a bench mark for further studies in tree-slope stability and landslide management relationships in Uganda and similar mountainous environments. Community will make use of the information for informed decision making on which tree species to plant in order to protect and restore their farmlands and increase the safety of their homesteads.

1.6 The role of vegetation in landslide control

Landslides occur as a result of numerous causative factors (Figure 1) which include; geomorphic, topographic, hydrologic, vegetation, geologic, meteorological, human and pedological factors (Zhao & Chen, 2020). These operate synergistically to cause landslides and therefore understanding each factor contribution is a significant milestone towards landslide management

(Devkota et al., 2013). Vegetation is the most important landslide causative factor during landslide risk management because it emerges as both a landslide control (Purwaningsih et al., 2020) when well managed and a trigger when mismanaged (Li et al., 2021). This results into a negative feedback or a positive feedback loop respectively a notion this paper focused on.

Vegetation in the negative feedback loop mechanism can be conceptualized as "*Planting a Right Tree in a Right Place"* and in positive feedback as *Planting a Wrong Tree in a Right Place*. Planting a right tree in a right is conceptualized as the act of planting specific trees with good characteristics of slope stabilization. Such characteristics may include ability to facilitate more runoff compared to infiltration in the process known as interception (Okello et al., 2015), accelerate evapotranspiration (Nakileza et al., 2017; Chirico et al., 2013) which enhances formation of well-drained soil surface horizon (Preti, 2013) and high shear and tensile strength by roots (Yu et al., 2020; Preti, 2013). Other root reinforcement characteristics may include tensile strength, root density, root depth, and root architecture (Lee et al., 2020). The root density and root architecture can be used to measure horizontal root reinforcement using index of root binding (IRB). These are known as the mechanical pathways of vegetation control. In contrary planting wrong trees in the wright place on the other hand means planting trees with poor slope stability characteristics thus exacerbating landslide formation. Yu et al., (2020) and Nakileza et al., (2017) explored some of the positive feedback mechanisms of trees and agreed that mature trees contribute to landslide formation through exerting addition weight on to already unstable slopes. Therefore, planting "*Right Trees in the Right Place"* after accurate prediction of landslides by considering each causative factor influence would produce a more affective landslides control plan.



Source: Adopted and modified from (Mulyono et al., 2018)

Figure 1: Study Conceptual framework

2. Methodology

2.1. Description of Study area

The study was confined in Tsume micro catchment, located on the upper slopes of Mt. Elgon. The micro-catchment stretches for about 93Km^2 (Figure 2) and it lies between latitude 0º 59` 0” N to 1º 7` 0” N and longitude 34º 21` 30” E to 34º 32` 0” E. Tsume comprises of various unique relief features such as the V-shaped valleys, sharp ridges and cliffs (Atuyambe et al., 2011). Specifically the Nusu ridge and Bukhalasi transect are characterised by many translational landslides (Makabayi et al., 2021; Claessens et al., 2007). The maximum altitude of the area is 4,226 meters and a minimum is 1,789 meters (a.s.l). The drainage comprises of rivers such as River Tsume, Ulukusi and Ukha which pour their waters in River Manafwa. The area experiences bimodal rainfall pattern with an annual precipitation of between 1000mm to 1600 mm (Opedes et al., 2022; Nakileza & Nedala, 2020). The mean average temperature ranges from 15˚C to 23˚C (Opedes et al., 2022; Graham et al., 2021; Mukadasi et al., 2007). In regards to vegetation, Tsume shares similar vegetation characteristics as the entire Elgon region. The vegetation is zoned altitudinally with montane forest types (Sebatta et al., 2020). Common indigenous tree species include

Markhamia lutea, *Albizia spp*., *Ficus spp*. and *Cordia africana* (Graham et al., 2021). *Yushania alpina* bamboo (Paul et al., 2015) is dominant in high zones and serves as a delicacy famously known as *Malewa* or *Maleya* to the local community. Socio-economically agriculture dominates the area with subsistence farming (Sebatta et al., 2020) characterized by coffee as the major cash crop grown on an agroforestry system of trees and bananas (Gram et al, 2018). In wet seasons, annual crops such as maize, beans, onions and cabbages are grown (Opedes et al, 2022). Onions are the second-best cash crop after coffee grown within the transboundary management areas of the park.

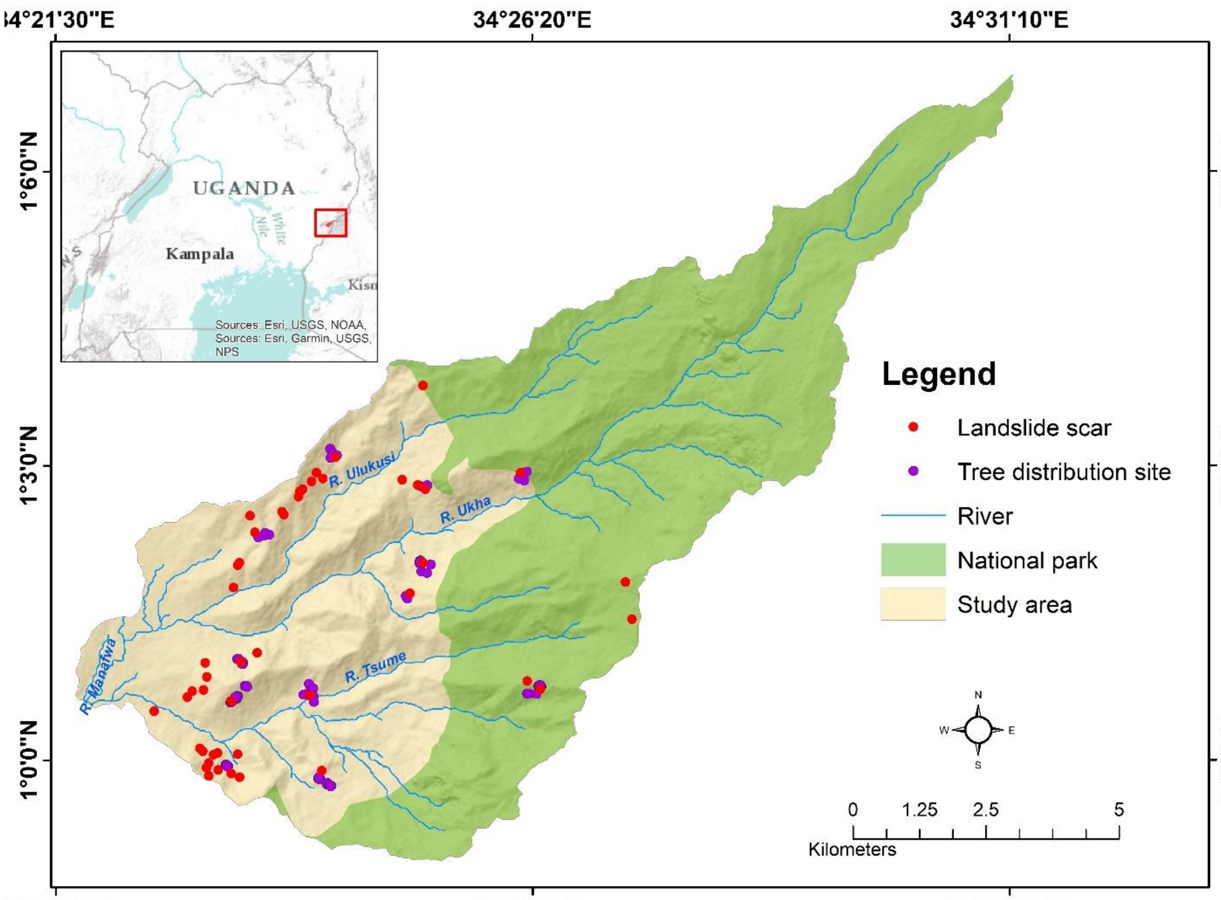


Figure 2: Location of Tsume micro catchment in Uganda

2.2. Methods and Material

2.2.1. Research Approach & Design

A quantitative research approach comprising of mapping surveys and experiments was used to achieve the study objectives. All research activities were concentrated in the very high-risk zones of the landslide susceptibility map and landslide scars. The landslide sampling frame was (*N=171*) scars clustered into two strata namely; landslide in the national park and landslides on community land using the Elgon National Park shapefile, as a classifier regardless of landslide size.

A stratified random sampling technique based on ArcGIS random sampling tool was used to generate sample elements (landslide scars) automatically. A total of (*n=12*) landslide scars was generated where 20 meters buffer was established. The buffer distance was informed by (Sofia & Afonso, 2019) who indicated that mature shrubs and trees can extend their roots up to $\geq$16 meter distance or as twice as their canopy. Given the high variations in landslide environmental conditions, size and depth across the study area, scars of area ($\leq$ 450m^3) and depth ($\leq$3m) were considered (Collins et al., 2012) and treated equally as much as possible (Burger et al., 2021). Identification of species, dbh measurements and mapping of agroforestry trees was confined within the 20m buffer.

For root tensile strength analysis, 9 samples (Osman et al., 2011) of saplings of each selected agroforestry tree species in the 20m buffer with a dbh $\leq$ 5cm (Hairiah et al., 2020) were randomly selected. Only roots with diameter $\leq$ 6mm were considered for tensile strength analysis (Nyambane & Mwea, 2011). This was because the available tensile strength apparatus could only manage small roots of diameter $\leq$ 6mm.

A total of 198 soil shear strength samples were randomly collected at an interval of $\leq$2m from the tree base. Of the total samples (168) were tested *in situ* and 30 were tested in lab for validation. Replicates (28) for *in-situ* and 5 for validation per species were carried out. Direct shear test was done from the lab in accordance with the ASTM D3080 standards (Rasti et al., 2021; Islam et al., 2021). Nevertheless, sampling was limited to only trees that met the tree selection criteria with 5 replicates per species.

2.2.2 Data sources

2.2.2.1 Mapping the spatial distribution of agroforestry tree species

Tree species selection

The criteria for selecting tree species for research included; dominant agroforestry species in the study area, well researched trees (e.g. *Calliandra* and *Cordia africana*) in regard to landslide control (Mulyono et al., 2018), and indigenous tree species such as *Markhamia lutea*. Focused Group Discussions (6) were held in different places (Munyende village, Ibookho, Bundesi primary school, Itimbwa, Nakhatore and Bukhalasi Primary school) to identify commonly planted agroforestry tree species (Figure 3). Details on FGD meetings are provided in Appendix 1. From the FGD *Cordia africana, Markhamia lutea, Croton macrostachyus, Grevellia robusta, Eucalyptus spp., Albizia coriria* emerged as the most planted trees thus considered for current research.

(a) FGD with male farmers in Ibookho village

(b) FGD with female farmers in Ibookho village

Figure 3: Focused Group Discussion with farmers during reconnaissance

Tree mapping

The landslide susceptibility and landslide scar maps were used to determine mapping areas. That is to say, the most susceptible areas and landslide scars were extracted and uploaded to QFIELD Mobile Application on TDC600 GPS to map all tree stands in the 20m buffer and their diameter at breast height (dbh). QFIELD is an open-source mobile application designed for mobile spatial data visualization and capture (Davies et al., 2006). The tool selection was based on Davies et al., (2006) criteria such as ability to run offline, operate on Android operating system, navigate to spatial features using device GPS, display spatial data, store data, capture geographic features among others.

2.2.2.2 Tensile strength and soil shear strengths data collection

Root sample collection for tensile strength analysis

Sampling sites were tracked using a TDC600 GPS and QFIELD mobile application. Using a hoe, a rake and a sharp knife, roots of selected agroforestry trees were carefully extracted from the soil as presented in (figure 4b-c). These were zipped in a plastic bag and labelled for subsequent analysis in the lab.

Root sample preparation

All roots from the field were cleaned and trimmed to 30cm (Figure 4d) for easy loading and storage. Defects such as physical damage e.g. breakage due to poor handling and root rot were inspected and removed from all samples. The clean samples were then stored in a deep freezer ≤ 0˚C to control biological processes such as decay and drying of the samples. All frozen samples were kept for only ≤ 36hrs and those beyond were discarded. The assumption was that those beyond the 36hrs had been affected by biological processes and therefore not fit for use since the study object was to test fresh roots.

Root loading

Root diameter at head and tail was taken using a digital Vernier calliper before loading. The Calliper has a measuring range of 150mm/6in and resolution accuracy of +/-0.01mm (Comino & Marengo, 2010). To reduce root damage by the apparatus clips and increase grip, all samples were wrapped with paper-based sole tape on both ends. The roots were then loaded on the developed tensile machine (apparatus) in the figure 4a. The apparatus comprised of the digital weighing scale (capacity = 50kg), wedge clips, and a vice that acted as the effort.

Soil sample collection for shear strength analysis

Figure 4e presents soil sampling for shear strength analysis. Cylindrical soil cores of 80mm internal diameter and 130mm height were used to collect undisturbed soil samples for shear strength analysis, contrary to Balzano et al., (2019) and Mugagga et al., (2012a) who utilized shear boxes with a square cutter. Cylindrical cores were opted due to the design of the shearing machine. Additionally, in-situ shear strength analysis was carried out using a Torvane (Pocket Vane Tester) as described by (Avunduk et al., 2021) and (Al-Rubaiee & Jajjawi, 2018). The measuring range of the torvane was (0 – 250) kpa and the adapter size for measuring was CL 100 = 1.0936 kg/cm² per complete revolution.

a) Tensile machine collection

b) Extracted root sample

c) *Cordia africana* root extraction

d) Trimming of Markhamia lutea root samples to 30cm for easy storage and loading

e) Field soil sampling

Figure 4: Sample collection and preparation for analysis

2.3. Data Analysis

2.3.1 Tree distribution and slope stability

Spatial distribution and direction of selected agroforestry tree species was analyzed using standard deviation ellipse method of ArcGIS (Zhao et al., 2022; Moore & McGuire, 2019; Wang et al., 2015). The method is widely used to explore spatial variation of geographic phenomenon and it provides centre of rotation, distribution, orientation and shape (Guo & Yuan, 2022). In this study species names were used as case file to measure agroforestry tree dispersion and orientation. Standard deviation factor 1 of variance was used to define ellipse size (Perzia et al., 2022).

Finally the relationship between tree distribution and landslide occurrence was achieved through Pearson's correlation method denoted in equation 1 (Pahlavani et al., 2017). Collins et al., (2012) has used correlation methods to test relationship between landslide occurrence and several factors such as slope, geology and earthquakes. Similarly in Uganda (Bamutaze, 2019) used correlation to test relationship between landslide occurrence and morphometric attributes. In this study landslide size (y-axis) and tree diameter at breast height (x-axis) was correlated.

$$r_p = \sum_i (x_i - \bar{x})\,(y_i - \bar{y}) \,/\, \sqrt{\sum_i (x_i - \bar{x})^2}\,\sqrt{\sum (y_i - \bar{y})^2} \;\ldots\ldots\ldots (1)$$

Where; $\bar{x}$ and $\bar{y}$ are the mean values of x and y respectively. r_p values range from -1 to 1 corresponding to negative or positive relationship and 0 indicates no relationship.

2.3.2 Tree species root characteristics for slope stability

Root reinforcement characteristics were determined by analyzing root tensile strength, Index of Root Binding (IRB) of soil and soil shear strength. According to Comino & Marengo (2010) effective root reinforcement can be measured through soil shear strength, root tensile strength and root architecture. Therefore, root tensile strength was expressed as a ratio of resistance and root area equation 2 which is measured as the ratio of maximum force applied to a root at the failure surface to its root diameter (Ettbeb et al., 2020; Lee et al., 2020). a one-way ANNOVA was conducted to test for differences within species.

$$T_r = {}^{4F}/_{\pi d^2} \ldots (2)$$

Where; T_r is the tensile strength, F is the maximum load at the rupture point (N) and d is the average roots diameter. Then the Index of Root Binding of soil (IRB) was calculated using equation 3 as proposed by Hairiah et al., (2020) expressed as:

$$IRB = \frac{\sum(DHR)^2}{DBH^2} \ldots . (3)$$

Where; DBH is tree diameter at breast height (1.3m height) and DHR is the diameter of the horizontal roots. However, this method was modified to mean diameter of horizontal roots and mean DBH presented in equation 4. The overall root reinforcement was determined using the soil shear strength calculated from equation 5 below (Yu et al., 2020; Ettbeb et al., 2020; Sofia & Afonso, 2019; Comino & Marengo, 2010) which then descriptive statistics followed

$$IRB = \frac{\sum(Mean\ Diameter\ of\ horizontal\ roots)^2}{Mean\ DBH^2} \ldots . (4)$$

$$S = \underset{\circ}{C} + C\varepsilon + \underset{\circ}{\sigma} tan \underset{\circ}{\delta} \ldots (5)$$

Where, S denotes the effective soil shear strength, $\underset{\circ}{C}$ is the soil cohesion, $C\varepsilon$ is the root reinforcement calculated from equation 6 (Fata et al., 2021), $\underset{\circ}{\sigma}$ is normal load (pa), and $\underset{\circ}{\delta}$ is the angle of internal friction in degrees.

$$C\varepsilon = T_r \left(\frac{A_r}{A}\right) (\sin\theta + \cos\theta \tan\emptyset) \ldots (6)$$

Where T_r is the tensile strength per unit area of roots, θ is the relative vertical deviation angle of roots subjected to shear deformation in degrees, A_r is the total cross-sectional area of all roots and A is the area of soil in the sample.

2.4 Environmental and Ethical consideration

Tensile strength assessment required one to uproot the entire plant to expose available roots, thus making this method destructive. To minimize such effects, only three roots were extracted from each sample element after a careful observation of the plant health. Plants exhibiting poor health or stunted growth were excluded from the study. Farmers consent prior root extraction was pursued verbally after informing them about the likely risks of giving out their trees for study. Then using a hoe and a sharp knife, roots were carefully dug out about 30cm away from the stem base.

A no plastic bag policy was also strictly adhered to by the researcher and his helpers to avoid or minimize plastic pollution of the ecosystem. Only reusable materials were utilized including metallic cans for carrying drinking water and sisal sacs for carrying soil samples. Root tensile strength were carried out in the field to avoid littering.

3.0 Results

3.1 Tree distribution analysis

A total of 129 trees were mapped from 12 selected landslide scars and of the total trees mapped, *Eucalyptus Spp* (28%) was the most abundant, followed by *Markhamia lutea* (23%), *Cordia africana* (15%), *Grevillea robusta* (14%), *Albizia coriaria* (12%) and *Croton macrostachyus* (8%). Species dispersion and direction results in Figure 5 showed *Croton macrostachyus* and *Markhamia lutea* as the most dispersed species in the study area. On contrary, *Albizia coriaria* was the most localized in the downstream. *Croton macrostachyus* was more dispersed to the western direction while *Markhamia lutea* was at the centre of the axis. *Albizia coriaria* and *Eucalyptus Spp* was dispersed towards the Southwestern direction while *Grevillea robusta* and *Cordia africana* to Northwest. The relationship between landslide size and tree diameter at breast height (DBH) revealed a weak negative correlation ($r = -0.20 < 0.01$) between the variables.

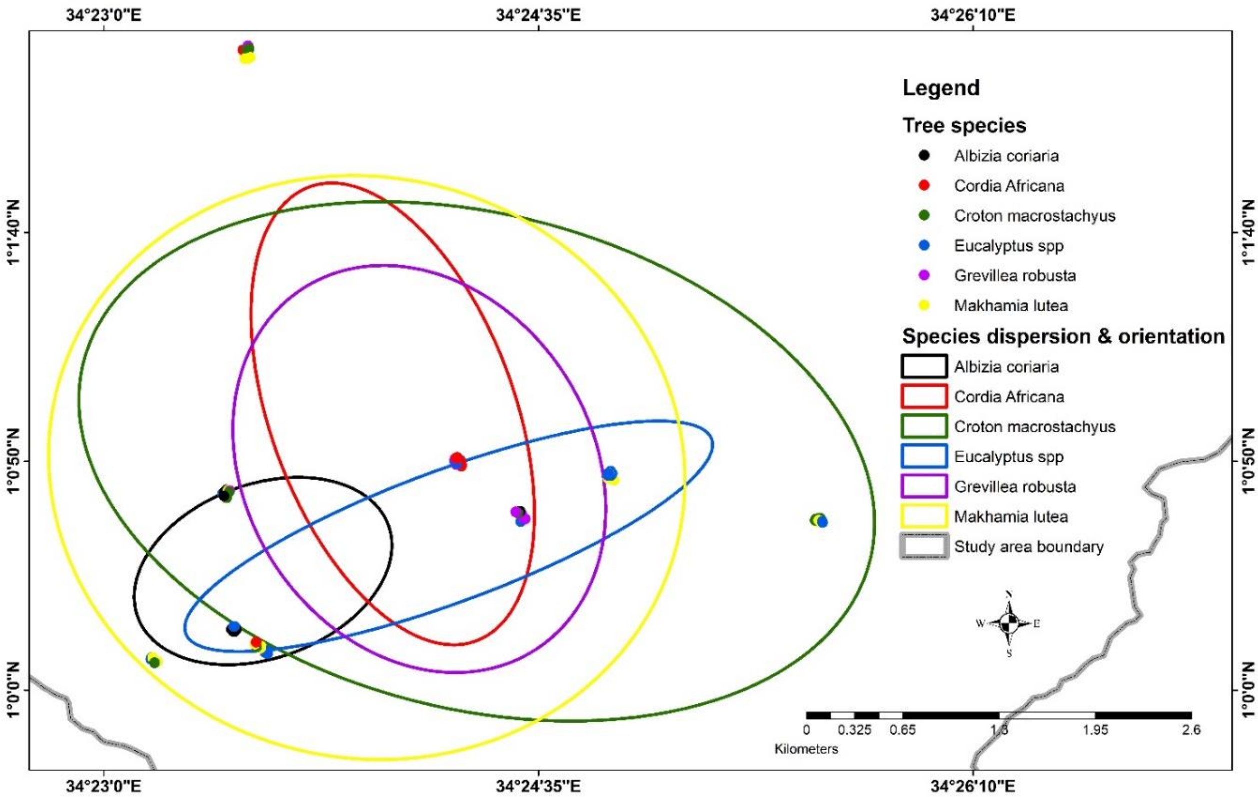


Figure 5: ***Standard deviation Ellipse showing dispersion and direction of selected tree species***

3.2 Root characteristics for slope stability

3.2.1 Tensile strength analysis

A one-way analysis of variance (ANOVA) was performed to compare root tensile strength of six (6) selected agroforestry tree species as a characteristic for consideration in adoption for slope stability. ANOVA results indicated that all species means were significantly different from each other with ($F(5, 573) = [18.161]$, $p < 0.001$). However, *G. robusta, A. coriaria,* and *M. lutea* had the highest tensile strength with average weight of 3.02±1.217kg/mm², 2.53±1.382kg/mm², and 2.28±1.01kg/mm² consecutively (Table 3). On the other hand, *C. macrostachyus* (1.78±1.167)kg/mm² and *C. africana* (1.69±1.153)kg/mm² had the least tensile strength. A scheffe post hoc criterion for significance confirmed variability within species as follows. The root tensile strength of *A. coriaria* (2.206±0.832) was significantly different from *G. robusta* ($p < 0.001$) and *M. lutea* ($p < 0.001$). Similarly, *C. africana* (3.065±0.872) was significantly different from *M. lutea* (5.096±0.358; $p < 0.001$). A same pairwise comparison also revealed that *C. macrostachyus*

(2.143±0.683) was significantly different from *Eucalyptus spp* ($p = 0.049$), *G. robusta* ($p < 0.001$), and *M. lutea* ($p < 0.001$). Finally, *Eucalyptus spp* (3.457±0.144) significantly ($p = 0.002$) differed from *M. lutea*. The index of root binding (Table 1) was highest for *A. coriaria* (81.31), and lowest for *M. lutea* (47.84).

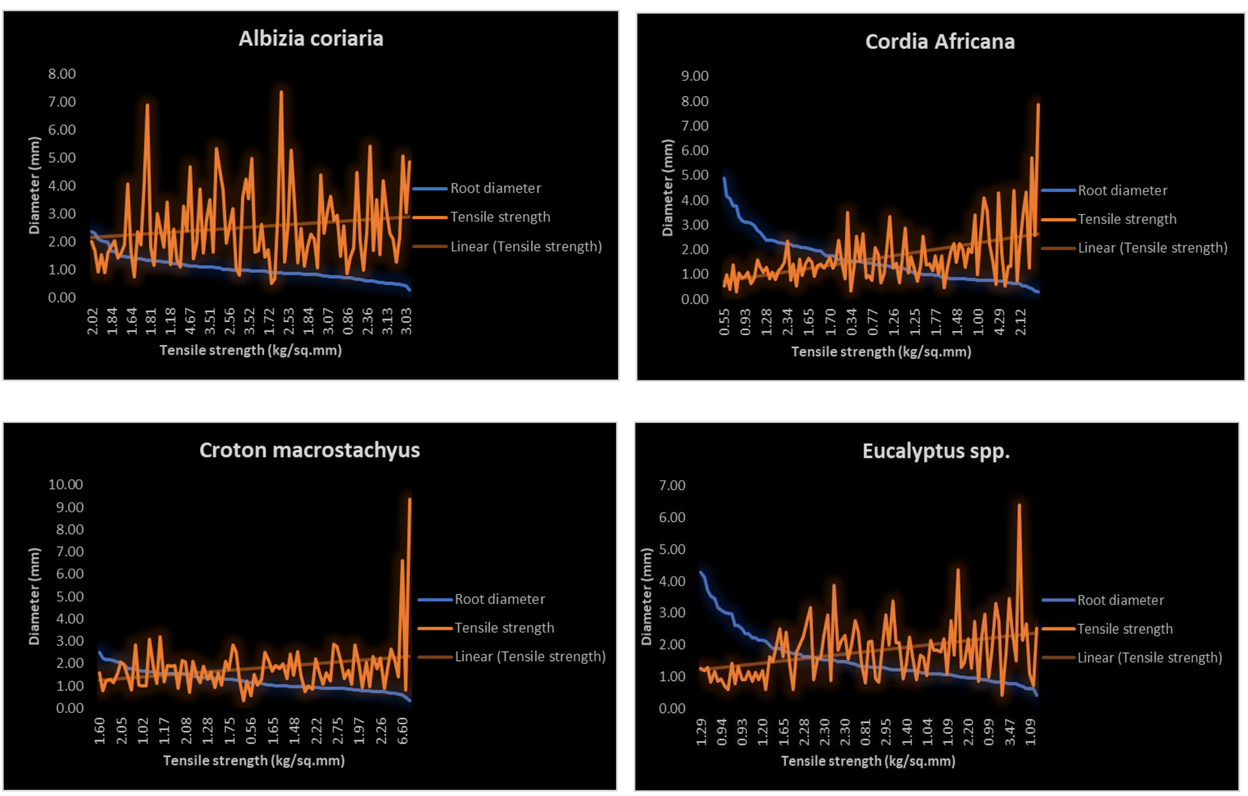
Table 1: Mean and standard deviation rapture weight (kg) of selected agroforestry tree species

Species	N	Mean weight (kg)	Std	Mean T_r(kg/sq.mm)	Std	*IRB*
Albizia coriaria	98	2.21	0.832	2.53	1.382	81.31
Cordia africana	105	3.10	0.872	1.69	1.153	69.90
Croton macrostachyus	87	2.14	0.683	1.78	1.167	51.69
Eucalyptus spp	99	3.50	0.144	1.80	0.926	58.87
Grevillea robusta	85	4.22	0.500	3.02	1.217	57.44
Markhamia lutea	105	5.10	0.358	2.28	1.013	47.84

N = number of samples, Std = Standard deviation, IRB = Index of root binding, T_r= Tensile strength

3.2.2 Root diameter verses tensile strength

As shown in figure 6, all species indicated an inverse relationship between tensile strength and root diameter. Sharp slopes were observed among *C. africana, G. robusta, Eucalyptus* Spp. and *M. lutea*.



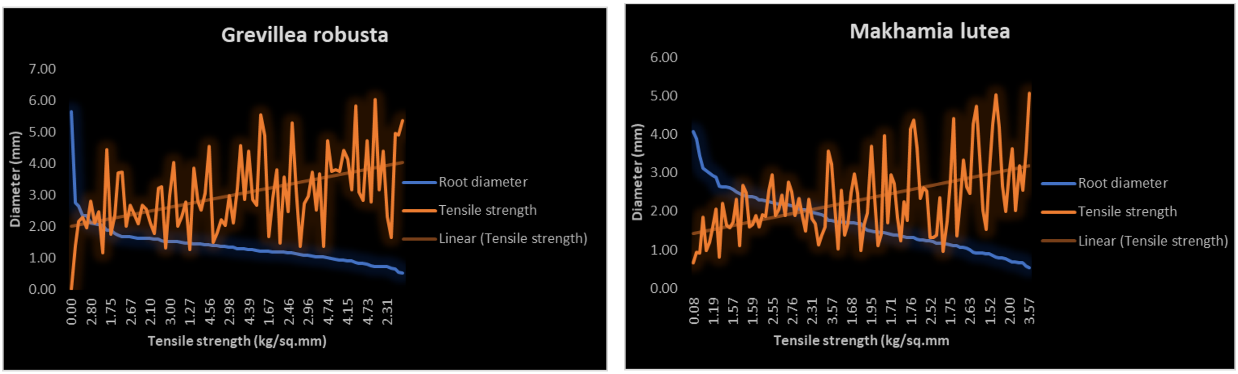


Figure 6: Root tensile strength-diameter relationship

3.2.3 Shear strength of selected agroforestry

Figure 7 presents average shear strength of selected agroforestry tree species under study. The best performing species in terms of shear strength was *Albizia coriaria* with average shear strength (52.46±10.24) kpa followed by *Markhamia lutea* (50.70±15.47) kpa. The worst performing species in shear strength was *Eucalyptus spp*. with average shear (46.75±12.92) kpa. However, no significant differences were observed among species.

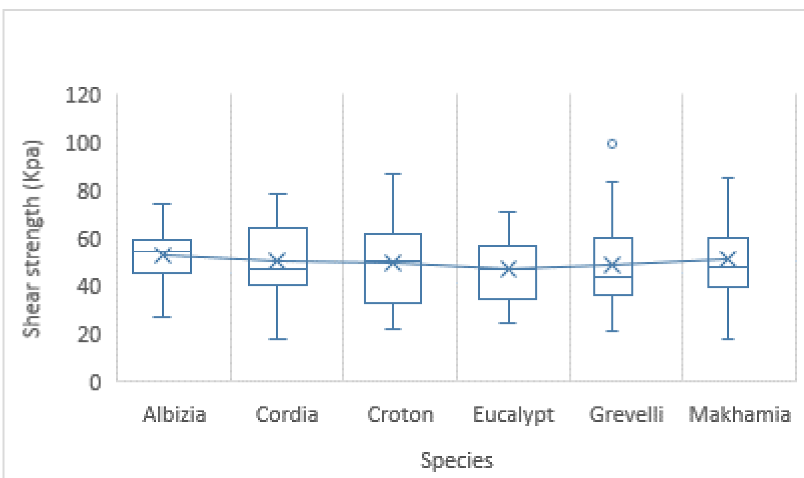
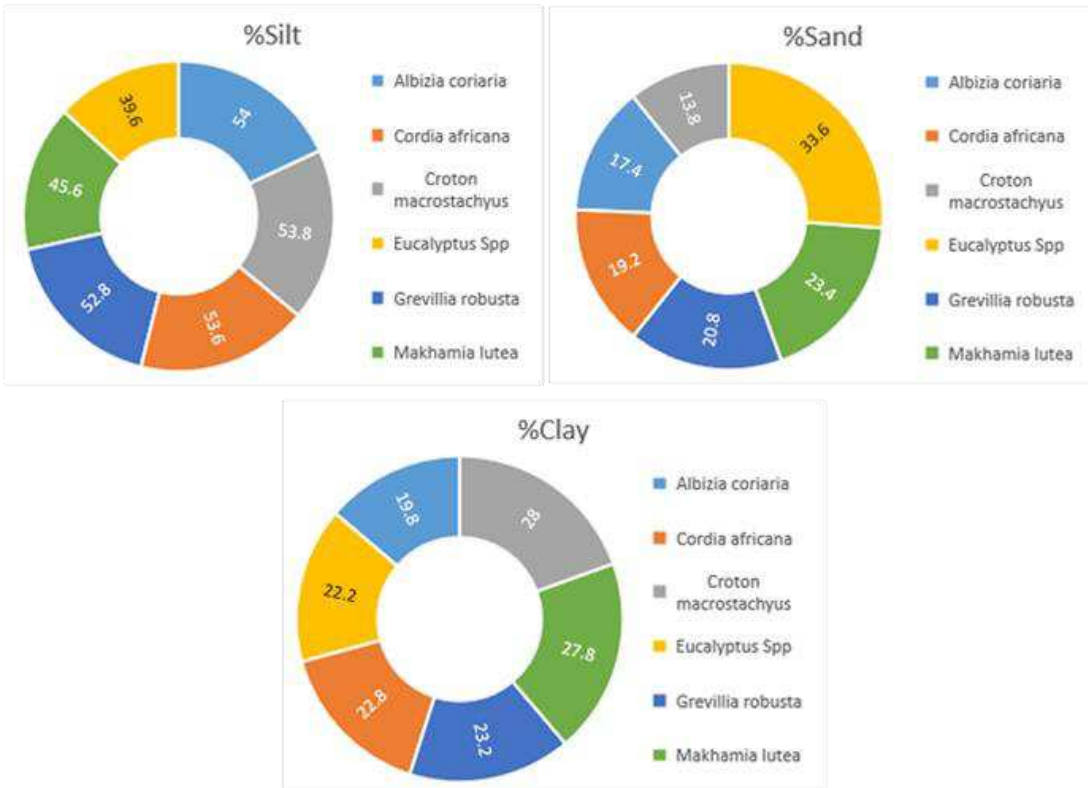


Figure 7: Box plot showing average shear strength of selected agroforestry tree species

3.2.4 Soil texture analysis for selected trees

Soil texture results as presented in Figure 8 indicate average highest clay content (27.8%) in soil samples picked near *Markhamia lutea*, sand (33.6%) in *Eucalyptus Spp* and silt (54.0%) in *Albizia coriaria* soil samples.

Figure 8: Percentage soil texture



4.0. Discussions

4.1 Landslides and tree distribution

The analysis of the relationship between landslides and tree distribution revealed an inverse relationship between landslide scar size and DBH. The results imply that presence of trees reduce landslide risk in an area and DBH is a very important factor. A study by Nelson et al., (2015) indicated that DBH (< 25 and > 60 cm) do not guarantee slope stability due to low factor of safety (< 1) while those within do. Yang et al., (2017) concluded that large trees (DBH > 20cm) reduce landslide risk for as far as 10m distance from the tree base. They further pointed out that much as large DBH may increase surcharge pressure downslope to weight of trunks, the net effect of large trees on slope stability is positive. The latter is true for lower landslide susceptibility in the Southwest direction of the LSM (high rather than very high) where *Albizia coriaria* was highly concentrated. The high concentration was due to high adoption by farmers in their coffee and banana systems as a result of promotion by Shunya Yettana CBO (Nakileza et al., 2017) and other players.

4.2 Root characteristics for landslide control

The study considered root characteristics as a feature for tree adoption to control landslides. A one-way ANOVA indicated high variability of tensile strength among species. The variability is as a result of environmental condition, species and age (Nyambane & Kinyua , 2011; Schmidt et al., 2001). Results also showed that *Grevillea robusta, Albizia coriaria,* and *Markhamia lutea* were the best performing trees with highest tensile strength. Strikingly *Cordia africana* was among the worst performers yet it had been widely promoted to farmers among the indigenous species for landslide control. According to Mugagga et al. (2015) *C. africana* is among good carbon sequesters thus the reason for its promotion. Nakileza & Tushabe, (2018) associated their adoption to tap root system that penetrate into deeper layers of the soil. Galabuzi et al., (2021) on the other side found that *Cordia africana* adoption was highly linked to good shed, firewood and timber. However, in contrary Graham et al., (2021) reported a low adoption of indigenous trees particularly *Cordia africana* and *ficus spp.* against exotic tree species such as *Eucalyptus* and *Grevilia spp.* among community.

Comparison among species indicated a significant difference between *Albizia coriaria* and *Grevillea robusta* ($p < 0.001$), *Albizia coriaria* and *Markhamia lutea* ($p < 0.001$); *Cordia africana* and *Markhamia lutea* ($p < 0.001$); *Croton macrostachyus* and *Eucalyptus spp* ($p = 0.049$); *Grevillea robusta* ($p < 0.001$) and *Markhamia lutea* ($p < 0.001$); and *Eucalyptus spp* and *Markhamia lutea* with ($p = 0.002$). A study by Hairiah et al., (2020) and Comino & Marengo, (2010) suggested that fibre and lignin content are factors that can explain tensile strength variations among species. For instance, Hairiah et al., (2020) found that lignin explained 70% of variations among species. A study by Senthamaraikannan et al., (2019) reported a high cellulose content (64.54 wt%) and low microfibrile angle in *Albizia amara* barks which offers high tensile strength (640±13.4 Mpa). They further reported low fibre density, a feature which could reduce surcharge weight on slope direction. However, an in-depth study is required to confirm this factor. Similarly Gopinath et al., (2021) studied *Albizia saman* cellulosic fibre content and tensile strength. Their results reported a 60.76 wt% cellulose, slightly lower than *A. amara* and a high tensile strength (381 – 1092 *Mpa*). Recently Madhu et al., (2022) reported (55.83 wt%) cellulose and tensile strength (483.40±18 Mpa) for *Albizia julibrissin*. The tensile strength results by Madhu et al., (2022); Gopinath et al., (2021); and Senthamaraikannan et al., (2019) were significantly higher than the current study because their test were conducted on dry samples. Also, the machine used for testing their tensile strength were highly developed compared to the current study. Of recent Hairiah et al., (2020) found a positive relationship between plant root nitrogen and tensile strength. These research findings further suggested that *Albizia coriaria* and *Cordia africana* had more advantage of holding soil unlike *Markhamia lutea*. According to Harahap et al., (2018) and Mulyono et al., (2018) trees with high IRB are well suited for slope stability than those with low IRB. During root extraction in the field, it was observed that *Markhamia lutea* had fewer roots compared to any other species and this could contribute to low IRB. Also, trunk volume was lowest compared to other trees which could have contributed to the observed results.

Finally shear strength results suggests *Albizia coriaria* as the best tree for slope stability followed by *Markhamia lutea* although the results were not significant. On the contrary *Eucalyptus Spp.* was the worst performing tree with lowest mean shear strength yet the most preferred and abundant tree due to its fast growing characteristics (Buyinza et al., 2021) and economic value Graham et al., (2021) and Nakileza et al., (2017). High silt and clay content recorded in soil samples collected near *Albizia coriaria* and *Markhamia lutea* would somehow account for the observed high shear strength in the two species while high sand content would explain the low shear strength in soil samples near *Eucalyptus spp*. This therefore suggests that not only roots affect shear strength but also other factors. According to (Hairiah et al., 2020) soil shear strength is also highly dependent on soil texture.

4.3 Conclusion

This paper presented on how the knowledge of DBH, tensile strength, index of root binding and soil shear strength could be harnessed in controlling landslide risk in Tsume micro catchment. The study observed that presence of trees reduced landslide risk in an area and DBH was a very important guiding factor. That is increase in DBH directly decreased landslide scar size and thus the risk. Results also suggested *Grevillea robusta, Albizia coriaria,* and *Markhamia lutea* as best Eco-engineering trees with high tensile and shear strength. On contrary *Eucalyptus Spp.* was the worst Eco-engineering tree with very low shear strength yet most abundant in the area. This explains the continued landslides burden despite several tree planting initiatives signifying that there is planting of wrong trees in the right place. The research findings further suggested that *Albizia coriaria* and *Cordia africana* had an added advantage of holding soil particles together unlike *Markhamia lutea* with low index of root binding.

4.4 Recommendation

Tree planting programs and campaigns in Bududa need to prioritize mixed planting of *Albizia coriria*, *Grevellia robusta* and *Markhamia lutea* on farm plots due to their good Eco-engineering characteristics as observed in this research. The trees need to grow up to a certain size (DBH ≥ 20cm) for full realization of the slope stability characteristics. However, a Regulatory Impact Assessment (RIA) towards establishment of an Effective Landslide Mitigation and Resilience Plan as part of DRR strategy aimed at promoting the above tree species by OPM in mountainous areas is required for a proper sensitivity analysis.

For future researchers, an in-depth tensile strength analysis using a modern tensile machine of higher capacity is highly recommended to test bigger roots for proper comparison of the results so as to increase confidence in the findings. This is because the current study utilized a simple rudimentary tensile machine which was limited to root diameter (≤ 6mm). Moreover, a similar investigation on other indigenous tree species, fruit trees, shrubs and grasses would be beneficial for widening the scope of other tree variates communities may prefer. Finally, further research is required to analysis the effect of tree species age on shear strength and slope to identify best tree combinations and age with optimum slope stability characteristics on different slope angles.

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