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DIRECT SHEAR TESTS ON ROOTED SOIL OF DISTICHLIS SPICATA AND KIKUYUOCHLOA CLANDESTINA

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ABSTRACT: The riverbank areas of the Arequipa region are periodically subject to landslides caused by seismic activity, natural changes in land structure, and climate-related factors. These events have significant social and economic impacts on the local population. Therefore, it is crucial to explore sustainable, efficient, and cost-effective methods for stabilizing slopes. One such method involves enhancing slope stability by increasing the shear strength of the soil through unconventional means. This study examines how adding roots from two perennial crops affects the shear strength of silty sand soils near a riverbank in Arequipa City. The study specifically focuses on Distichlis spicata and Kikuyuochloa clandestine crops, which have extensive root systems developed through stolons. Physical characterization tests were carried out on two samples of silty sand along with direct shear tests using different values of root area ratio at various depths to assess soil-root interaction parameters comprehensively. The test results indicate that both Distichlis spicata crop and Kikuyuochloa clandestina crop alter the soil's shear strength by increasing the friction angle. The modification of cohesion depends on the specific type of crop as well as soil characteristics. Thus, both crops decrease cohesion in one type of soil and increase it in the other one. It can be concluded that integrating these crops into soils significantly enhances their maximum shear stress under elevated normal stresses, thus improving slope stability overall.

Keywords: Direct shear test, Shear strength, Perennial crops, Root architecture, Root area ratio

1. INTRODUCTION

The eastern side of the Peruvian Andes Mountains range experiences a dry temperate climate with limited rainfall and periodic events such as the El Niño phenomenon, which brings high-intensity rains causing slope landslides.

Landslide phenomena have been the subject of extensive research in geotechnics' field, with specialists responsible for evaluating their stability and determining appropriate processes or methods that provide protection against some failure type or movement of soil mass. One proposed method involves bioengineering and environmental geotechnics, which suggests reinforcing the soil mechanically by adding roots to enhance slope stability [1-2].

Plant roots play a crucial role in protecting slopes against intense rains by enhancing shear strength through apparent cohesion. Various authors have conducted direct shear tests on rooted soils to demonstrate how root presence increases soil shear strength by influencing tensile strength and root size [3-5]. Wang and Wang [6] presented evidence suggesting that the existence of plant roots is associated with an augmentation in soil shear strength, which contributes to improved slope stability. The involvement of plant roots is a critical factor in bolstering slope stability through the increase in soil shear strength.

While studies on this topic have been predominantly carried out in North America, Europe, Asia, Oceania, and Brazil [7], no previous research has been identified in Peru. Table 1 summarizes the previous studies conducted on different crops and soils, along with the key findings from direct shear tests conducted both in the laboratory and in the field by several researchers.

Therefore, this study aims to contribute to knowledge about two perennial crop species, Distichlis spicata and Kikuyuochloa clandestine, that grow on natural slopes along riverbanks in Arequipa, Peru and their impact on regional soil shear strength. The study investigated the influence of roots from two different crops on the soil's shear strength in a sloped area near a riverbank in Arequipa. The research included a thorough physical-mechanical assessment of the crops, considering factors such as root area ratio, root length, average root diameter, and other relevant parameters. This investigation aims to uncover correlations between soil-root interaction and soil shear strength to yield important findings for sustainable land management and landslide control in similar geotechnical settings.

2. RESEARCH SIGNIFICANCE

The study results will help us confirm that the roots of Distichlis spicata and Kikuyuochloa clandestina species can enhance the shear resistance of surface soils on slopes. This supports the idea that these species play a positive role in stabilizing slopes along Peruvian riverbanks. Cultivating these species presents a sustainable, eco-friendly, and cost-effective bioengineering solution to mitigate recurrent landslides caused by rainfall in Peruvian river areas. Also, it is a positive contribution to alleviating climatic change.

3. EXPERIMENTAL PROGRAM

3.1 Study Area

The study area is a slope in a Socabaya riverbank, located in the Socabaya district of Arequipa, Peru, is primarily composed of alluvial and colluvial soils such as gravel and sand [17]. According to research by [10,13,15], the soil in this area would be suitable to implementing the root addition method.

Additionally, it was important to consider the geometric characteristics of the slope based on studies by [18] as well as [19]. The studied slope has an average height of 25 meters with a variable slope ranging from 35% to 85% over a length of 300 meters; at its crown are houses belonging to the Santa Cruz de Lara and Villa Santa Cruz housing associations (Figure 1).

3.2 Sampling and Characterization of Soils

Sampling activities in the field encompassed the excavation of 5 pits on the slope, with 2 situated at the top, another 2 at the bottom, and one positioned in the central area. This process adhered to Peruvian standard [20]. Disturbed soil samples were collected from these pits and placed in plastic bags, while undisturbed soil samples were acquired in blocks as outlined by Peruvian standard [21]. Geotechnical tests were conducted to assess the properties of the soil samples obtained.

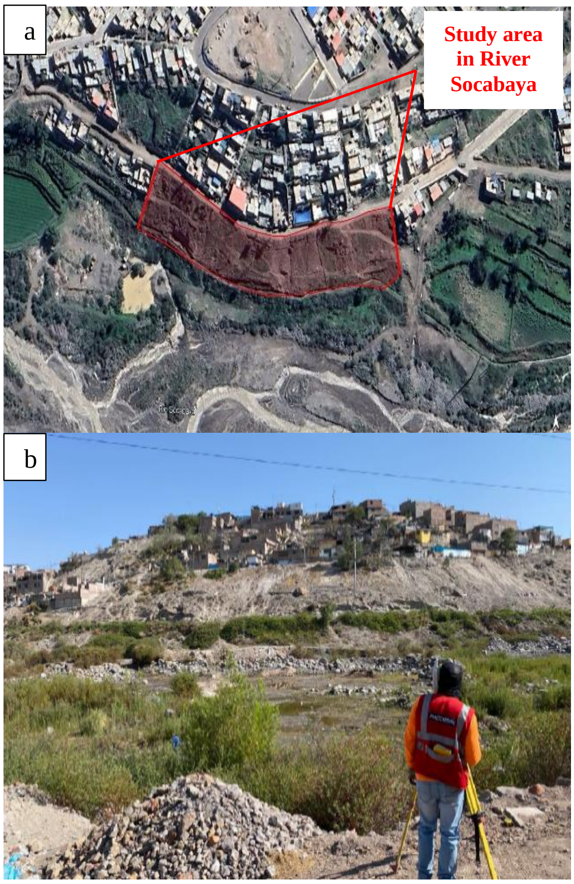

Fig. 1 Study area (a) map, (b) slope view

Table 1 Studies on direct shear testing of rooted soils

Authors	Crop	Soil type	Results		
			RAR (%)	Δc' (kPa)	Δø' (°)
Laboratory testing					
Wang et. al. (2020) [8]	Pasto vetiver	Expansive soil (China)	-	181.81	17.23
Tan et. al. (2019) [9]	Geotextile with Bermuda grass	Silty clay (China)	-	20.00	2.1
Jaskulski (2018) [10]	Esmeralda grass	Alluvial sandy soil (Brazil)	1.5	-	14.48
Islam and Badhon (2017) [11]	Vetiver grass	Coarse and medium sand (Bangladesh)	3	-	1.2
Passos and Gil (2017) [12]	Vetiver grass	Silty and clayey sands (Colombia)	-	60-23	5-9
Hytiris et. al. (2015) [13]	Common grass	Well graded sand (Scotland)	-	10	-
Cazzufi et. al. (2006) [14]	Eragrass, Elygrass, Pangrass & Vetiver	Clay (Scotland)	-	2-15	-
Field testing					
Maffra (2018) [15]	Phyllanthus sellowianus	Alluvial sandy soil (Brazil)	-	3.14	2.4
Rajan et. al. (2017) [16]	Karanj, Shisham, Neem, Sal, Kendu, Amla, Jamun, Banyan & Krishnachura	Iron ore mining waste (India)	-	30	2

Note: RAR = root area ratio; Δc' = cohesion increase; Δø' = friction angle increase

3.3 Physical Characterization of Crops

Two species were identified in the study area based on recommendations from [22]. These recommendations involve considering three criteria: biotechnical (crop characteristics based on stabilization requirements), environmental (climatic conditions and soil typology), and phytosociological (ability to adapt to the environment). The taxonomy of these species is Kikuyuochloa clandestina and Distichlis spicata.

Kikuyuochloa clandestina is a grass species native to Africa, belonging to the Poaceae family, with growth occurring through its rhizomes and stolons that easily root in the nodes of the stolons. This makes it highly adaptable to any type of soil [23]. On the other hand, Distichlis spicata is a perennial herbaceous species belonging to the Poaceae family, native to America. It generally grows along farm roadsides, hillsides, and near streams as it can thrive in unsuitable conditions for most plants such as high soil salinity and extreme droughts [24].

These perennial plants propagate using underground stems known as stolons, and they thrive in environments with high humidity. After identifying these two plants species, the roots were carefully extracted by hand to avoid damaging the main roots or cutting them accidentally. Five individuals from each species were selected for a study on their variability in root dimensions, including length at different depths, which was measured using vernier calipers (as illustrated in Figure 2). In addition to this, photographs were taken with reference measurements to scale the images and assess the root architecture for more accurate root area ratio (RAR) calculations represented as a percentage within cross-sectional soil areas.

Fig.2 (a) Distichlis Spicata; (b) Kikuyuochloa clandestina

3.4 Sampling of Rooted Soil Blocks

Soil blocks containing the crops under study (aerial and root parts) were extracted from areas near the pits to ensure their development in the identified soils. Wooden containers with black polyethylene films at the base were set up for depositing these samples. This method ensured that necessary roots were available for direct shear tests, with interday irrigation helping maintain firmness and rigidity of plant cells (turgor) [1].

The process can be summarized as follows:

- Defining extraction zones approximately 40 cm long and wide, then creating trenches along the boundaries through manual digging to a depth of around 25 cm.
- Using a rod to apply pressure on the lower part of each specimen in order to detach it from surrounding soil.
- Gently extract and place each block in wooden containers filled with native soil at the base.
- Adding natural soil into the containers until exposed roots are covered, followed by watering to maintain moisture levels during transportation.

3.5 Direct Shear Testing

The soils containing roots were evaluated using the direct shear test under consolidated drained conditions [25].

The experiment involved testing soils with varying amounts of plant roots, both with and without roots. The soil was sieved through a No. 8 mesh and reconstituted samples were prepared to match the density and moisture levels found in the field. Subsequently, the specimens were subjected to loads of 2 kg, 4 kg, and 8 kg in a shear box with an area of 35.94 cm^2 (resulting in vertical pressures of 54.57 kPa, 109.14 kPa, and 218.29 kPa), while maintaining a specimen height within (25±0.7) mm range. The objective of the test was to assess how root content affects soil behavior by using reconstituted samples containing different percentages of roots.

The root inclusion approach for direct shear test execution, based on research by [10,13,14] is outlined in Figure 3. The process included:

- Choosing plants, removing aboveground biomass, cleaning roots to eliminate soil residues, and drying them on absorbent paper.
- The root area ratio was calculated, and roots with specific diameters were selected and cutted to a height of 2.5 cm to match the height of the shear box and ensure accurate testing.
- Placing a layer of soil in the shear box and gently compacting it using a tamper before positioning chosen roots at an inclination between 45 and 60 degrees to replicate the

arrangement of agricultural root networks. (Fig. 4).

- Adding a second and third layer with corresponding compaction until the density reaches the in situ value.
- Execute the direct shear test with a speed of 0.2 mm/min, which is suitable for silty sands.
- Counting and measuring root diameters passing through the failure plane post-test using vernier calipers to determine actual RAR.

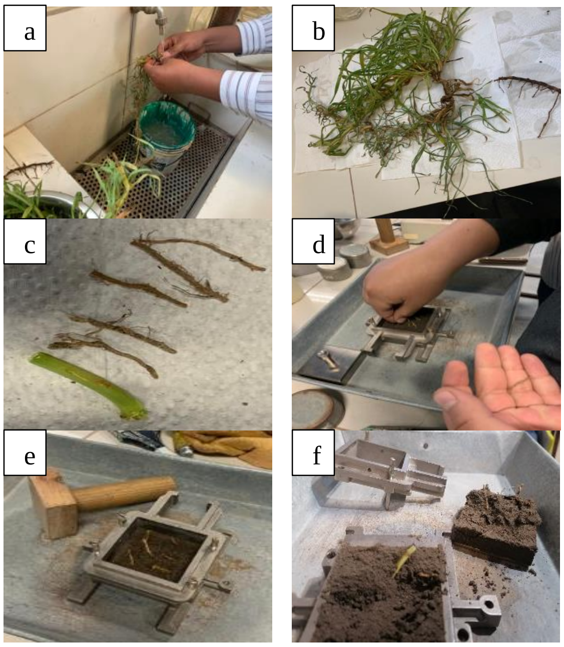

Fig.3 Rooted soil sample preparation for direct shear test: (a) Roots cleaning, (b) Roots dying, (c) Roots selection, (d) Placing roots diagonally and randomly, (e) Compaction of second soil layer, (f) Rooted soil specimen after testing.

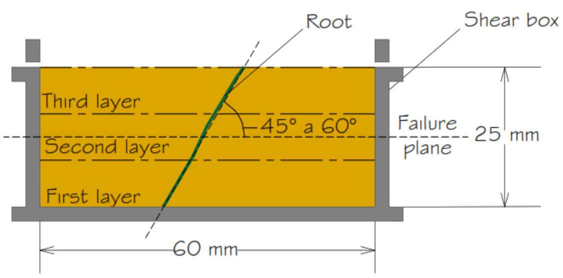

Fig. 4. Root configuration details within a soil specimen in a shear box.

4. RESULTS AND DISCUSSIONS

4.1 Physical-mechanical Characterization of Soils

Based on the granulometric analysis [26] and soil classification [27], two types of soil have been identified: Soil 1 is categorized as silty sand (SM), while Soil 2 is classified as silty sand with gravel (SM). Both soils are considered suitable for the method's application. It is important to highlight that the soil samples did not exhibit any plasticity during testing for Atterberg limits determination. For the direct shear test, it is noteworthy that the materials used passed through sieve number 8 (2.36 mm). The results of the physical characterization are presented in Table 2.

Table 2 Physical parameters of soils

Parameters	Soil 1	Soil 2
Water content (%), NTP 339.127 [28]	21.83	1.79
Gravel (%)	5.24	28.52
Sand (%)	67.78	58.72
Silt (%)	25.36	12.40
Clay (%)	1.62	0.36
Specific gravity Gs, NTP 339.131 [29]	2.61	2.64
Bulk density (gr/cm^3), ASTM D4531-86 [30]	1.56	-
Void ratio	0.979	-
Friction angle (°)	30.40	36.81
Effective cohesion (kPa)	24.35	2.6

Note: The density 1.56 gr/cm^3 was used for all the specimens.

4.2 Determination of Physical Parameters of the Root System

The root area ratio was computed for each individual and at each depth ranging from 0.10m to 0.10m using the Eq. (1) proposed by [31].

$$RAR\ (\%) = \frac{A_R}{A_T} \times 100\% \quad (1)$$

Where: RAR is root area ratio, A_R is root area, A_T is the fraction of soil cross-sectional area

A soil section of 0.30m x 0.10m was chosen to calculate RAR, considering that the crops grow through stolons and maintain a consistent width or thickness as they develop. The procedure (Fig. 5) involved creating root architecture graphics using drawing software based on measurements from referenced crop photographs, identifying the area with the highest root density for scaling and constraining graphs using grids with defined intervals, and determining the depth of failure planes at midpoint depths previously described (0.05m, 0.15m, 0.25m) and then proceeded to count the roots for each assumed failure plane.

In each type of crop, the individual with the highest number of roots within specified depths was chosen as it offers optimal conditions for the method.

Specific diameter categories were established for each depth by taking into account the variation in average diameters for each individual of the species. This facilitated conducting precise direct shear testing using estimated root numbers and their respective diameters to replicate real-world field scenarios. Table 3 illustrates diameter classes for each depth and crop alongside the proportion of roots within each class.

The estimation of the root quantity was derived from the proportion of roots within each diameter class, using data from the shear box section (approximately 36 cm^2).

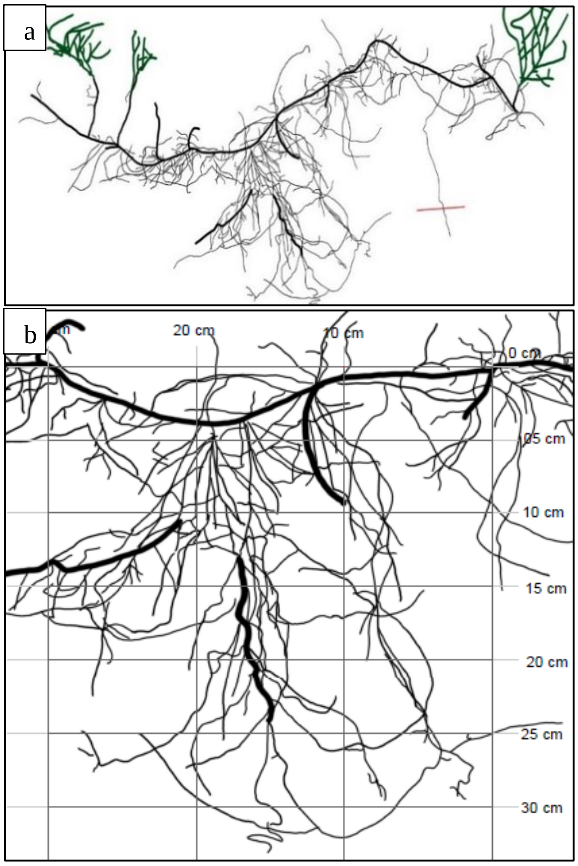

Fig.5 Clandestine Kikuyuochloa species scaled every 5cm for RAR determination (a) Root architecture graph, (b) Grids with depth intervals for graphs reference.

4.3 Direct Shear Testing

From the results, we can decipher various interactions between the two soils and the crop roots. It was decided to add 1 to 2 extra roots in order to maintain similar RAR conditions in all direct shear tests. As a result, the actual RAR was calculated at the end of each test, and an average value for each depth from the three tested specimens was considered. Therefore, Table 4 and Table 5 provide a summary of the shear strength parameter results, friction angle (ø') and cohesion (c'), for both soils with added Kikuyuochloa clandestina and Distichlis spicata crop roots at different RARs and depths that were assessed. The reveal that the RAR values for each crop and depth display consistency, irrespective of the soil type, leading to reliable results.

Table 3 Percentage of roots by diameter class and depth for each crop

Depth (m)	Failure depth (m)	N° roots indivi-dual	Diameter classes (mm)	% Roots by diameter classes
Kikuyuochloa clandestina				
0 - 0.1	0.05	31	0.5 - 1	10%
			1 - 1.5	70%
			3.5 - 4	20%
0.1 - 0.2	0.15	24	0.5 - 1	75%
			1.5 - 2	12.5%
			5 - 5.5	12.5%
0.2 - 0.3	0.25	15	0.5 - 1	85%
			4.5 - 5	15%
Distichlis spicata				
0 - 0.1	0.05	21	0.25 - 0.5	20%
			0.5 - 1	80%
0.1 - 0.2	0.15	3	0.25 - 0.5	50%
			0.5 - 1	50%

Note: The individual with the greatest number of roots was chosen

Table 4 Shear strength parameters for Soil 1 and Soil 2 with the addition of roots from the Kikuyuochloa clandestina crop

Depth (m)	RAR (%)	Water content (%)	Dry density (gr/cm^3)	Void ratio	Shear strength parameters	
					ø' (°)	c' (kPa)
Soil 1						
0.00	0	18.43	1.325	0.970	30.4	24.4
0.05	0.407	20.18	1.253	1.083	39.5	11.2
0.15	0.707	20.86	1.276	1.046	36.6	6.9
0.25	0.512	20.51	1.252	1.084	30.6	21.5
Soil 2						
0.00	0	3.91	1.386	0.905	36.8	2.6
0.05	0.441	4.71	1.309	0.993	32.3	17.0
0.15	0.767	5.25	1.293	1.018	36.7	14.8
0.25	0.514	4.50	1.325	0.969	36.7	2.3

Note: Depth 0.00 corresponds to soil without roots.

Figure 6 illustrates the RAR variation with depth for both evaluated species based on the scheme proposed by [32]. The Kikuyuochloa clandestina crop shows an increase in RAR between depths of 0.05 m and 0.15 m before decreasing, indicating that the optimal RAR value fluctuates within these depths. On the other hand, for the Distichlis spicata crop, RAR notably decreases with depth; suggesting that this crop's optimal RAR value lies at a depth of 0.05 m. Similar results were found by [32], in which the RAR of shrub species decreases with depth.

Table 5 Shear strength parameters for Soil 1 and Soil 2 with the addition of roots from the Distichlis spicata crop

Depth (m)	RAR (%)	Water content (%)	Dry density (gr/cm^3)	Void ratio	Shear strength parameters ø' (°)	Shear strength parameters c' (kPa)
Soil 1						
0.00	0	18.43	1.325	0.970	30.4	24.4
0.05	0.104	20.65	1.276	1.045	38.1	10.3
0.15	0.030	19.94	1.269	1.057	37.6	6.9
Soil 2						
0.00	0	3.91	1.386	0.905	36.8	2.6
0.05	0.079	4.48	1.304	1.002	40.5	4.1
0.15	0.032	4.10	1.296	1.014	36.4	14.2

Note: Depth 0.00 corresponds to soil without roots.

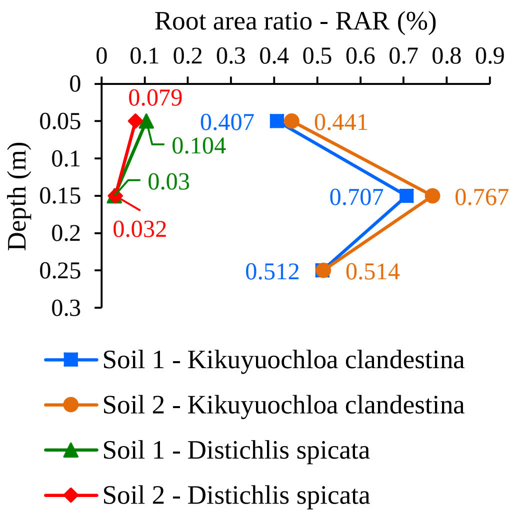

Fig.6 Root Area ratio (RAR) distribution with soil depth

4.3.1 Kikuyuochloa clandestina

According to the results, adding roots from the Kikuyuochloa clandestina crop increased the friction angle by 30% and 20% for RAR values of 0.407% and 0.707%, respectively, in soil 1. However, there was practically no variation observed for an RAR value of 0.512%. In contrast, in soil 2, there was a decrease of 12% in the friction angle for an RAR of 0.441%, while no variation was observed for RAR values of 0.767% and 0.514%.

In terms of soil cohesion, incorporating roots from the Kikuyuochloa clandestina plant into soil 1 resulted in reductions of 54%, 72%, and 12% for the RAR values of 0.407%, 0.707%, and 0.512% respectively. Meanwhile, in soil 2, it led to an increase in cohesion by 14.4 kPa and 12.2 kPa for the RAR values of 0.407% and 0.707% respectively; whereas there was almost no change observed for the RAR value of 0.512%.

Figure 7 illustrates the variation of the maximum shear stress in relation to the normal stress applied in each specimen of the direct shear test for every RAR and soil under evaluation. It is observed that there were increases in the shear stress of soil 1 and soil 2 for all cases of normal load when considering Kikuyuochloa clandestina crop.

When added roots from Kikuyuochloa clandestina, soil 1 shows a significant increase of 41.65 kPa with a normal stress of 218.29 kPa and a RAR of 0.407%; while soil 2 exhibits a significant increase of 18.6 kPa with a normal stress of 109.14 kPa and a RAR of 0.514%.

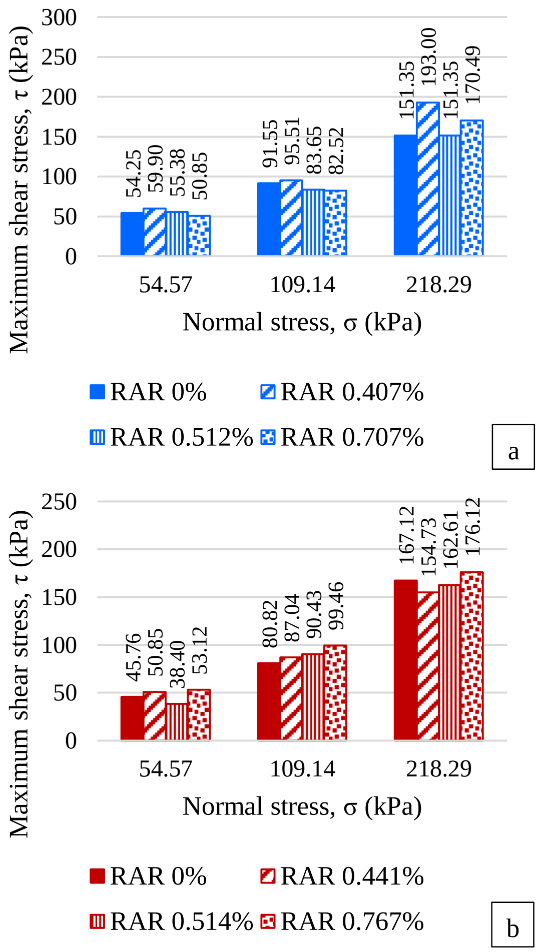

Fig.7 Variation in the maximum shear stress based on the RAR of Kikuyuochloa clandestina crop for (a) Soil 1 and (b) Soil 2

Figure 8 displays the distribution of roots by diameter class in relation to depth, as determined following the direct shear test. It is evident that the Kikuyuochloa clandestina crop performs well in soils where roots with diameters between 0.5mm and 1.5mm thrive, as these diameter classes exhibit the highest incidence at depths where greater increases in shear resistance are observed.

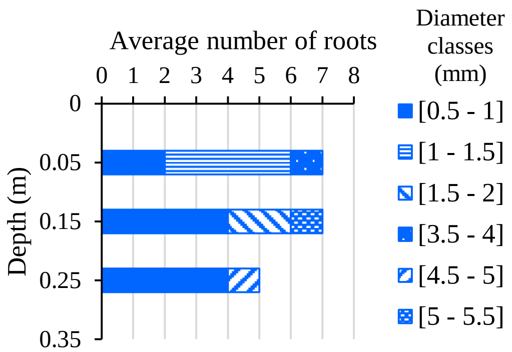

Fig.8 Distribution of roots by diameter classes at different depths for Kikuyuochloa clandestina

4.3.2 Distichlis spicata

The results indicate that adding roots of Distichlis spicata crop increased the friction angle by 25% and 24% for RARs of 0.104% and 0.03%, respectively, in soil 1. In soil 2, the friction angle increased by 10% for the RAR of 0.079%, while there was no variation for the RAR of 0.032%.

In soil 1, the incorporation of roots from the Distichlis spicata plant caused a reduction in cohesion by 58% and 72% for RARs of 0.104% and 0.03%, respectively. In the second type of soil, it resulted in an increase in cohesion by 1.5 kPa and 11.6 kPa for RARs of 0.079% and 0.032%, respectively.

Figure 9 shows the changes in maximum shear stress in relation to the normal stress applied during each specimen's direct shear test for both RAR and sampled soil. It is clear that there were increases in shear stress observed for all normal load cases when testing with Distichlis spicata crop, both for soil 1 and soil 2.

In soil 1, the presence of Distichlis spicata leads to a significant rise of 30.4 kPa under normal stress conditions of 218.29 kPa and a RAR of 0.104%. Conversely, in soil 2 there is an observable increase of 24.75 kPa under comparable normal stress levels and a RAR of 0.079%.

Figure 10 depicts the distribution of roots by diameter class in relation to depth for Distichlis spicata crop. It was observed that roots with diameters ranging from 0.5mm to 1mm exhibit strong performance in soils. This is attributed to their high occurrence at depths where significant increases in shear resistance are experienced.

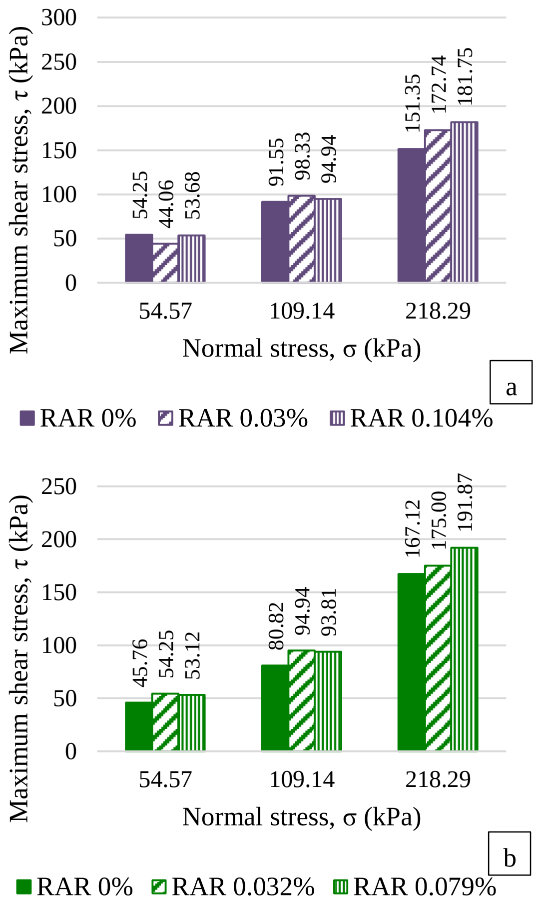

Fig.9 Variation in the maximum shear stress based on the RAR of Distichlis spicata crop for (a) Soil 1 and (b) Soil 2

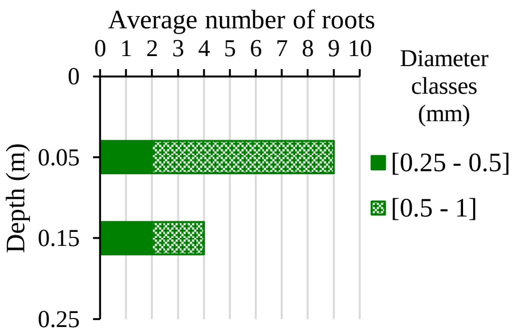

Fig.10 Distribution of roots by diameter classes at different depths for Distichlis spicata

Figure 7 and 9 indicate that soil samples containing Kikuyuochloa clandestina roots showed a 67% increase in shear strength compared to samples without roots. Similarly, the presence of Distichlis spicata roots resulted in an 83% improvement in shear strength for the soil samples. RAR showed a consistent link with the growth in shear strength in the majority of cases, but this connection was not observed in a small number of tests. This variance may be due to factors such as unaccounted physical-mechanical properties of the root, including its roughness and performance in pull-out tests, among others.

Root reinforcement has the potential to enhance soil shear strength by considering root morphology [33]. Additionally, the density of roots (expressed as RAR) plays a significant role in influencing the magnitude of increment in soil shear strength, supporting findings by [34]. These results demonstrate the advantageous impact of root reinforcement from Kikuyuochloa clandestina and Distichlis spicata on soil shear strength.

5. CONCLUSIONS

The two species studied, Kikuyuochloa clandestina and Distichlis spicata, have suitable characteristics in terms of their root system, growth, and strength for the proposed technique. It is evident that the method's performance is influenced by the morphology of the roots. The test results indicate that both species increased soil shear strength. Notably, Distichlis spicata demonstrated a more effective increase in shear strength compared to Kikuyuochloa clandestina crops.

It was observed that RAR decreases as the depth increases, which is a typical behavior of root systems. The depth and RAR are directly proportional up to a certain point, after which the RAR decreases until it reaches zero.

Tests have confirmed that the soils on the slope under study are suitable for the intended soil reinforcement technique. Incorporating plant roots into the analyzed silty sand soils has been shown to enhance its shear strength, leading to improved slope stability. Consequently, introducing both species' roots into these two types of soil results in notable improvements in maximum shear stress at elevated normal stresses.

In order to effectively implement the technique, it is crucial to initially examine the physical and mechanical characteristics of soil and roots. This analysis will provide insight into the level of reinforcement needed and its influence on slope stability. Furthermore, for future investigations, it would be beneficial to evaluate the properties of the plant's root system during its growth stages by performing in situ direct shear tests at varying ages of the roots and performing pull-out tests.

6. ACKNOWLEDGMENTS

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