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Stabilization of sandy slopes reinforced with Vetiver roots.

Estabilización de taludes arenosos reforzados con raíces Vetiver.

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ABSTRACT: The use of vegetation in slope stabilization is an alternative used to prevent superficial failure and landslides. However, this technique is not extended in Peru, mainly due to the lack of procedures to quantify properly soil improvement by the incorporation of roots, limiting the application of this technique. This research is focus on the use of Vetiver roots (Chrysopogon Zizanioides) to stabilize sandy slopes. The main feature of this root is the length and thick root system that allows Vetiver to extend up to 4 meters deep. To analyze the effects in slope stabilization of soils three, different geometry slopes were modeled with and without a layer of Vetiver with different values of cohesion and friction angle that characterizes the shear parameters of influence of the rooted soil with vetiver. Additionally, the factor of safety was compared in each case to obtain a range of improvement of the rooted soil.

KEYWORDS: Soil stabilization, sand, vetiver roots, cohesion, friction angle, factor of safety.

1 INTRODUCTION.

Vegetation is an alternative in slope stabilization that have a great potential in prevention of superficial failure and landslides. The incorporation of roots in the soil changes the mechanical parameters, altering the behavior of the top layer of soil (Wu 2013). When vegetation growths, their roots integrate the soil layers, generating a matrix root-soil. On this matrix, the roots increase the cohesion of the soil, improving the shear behavior, while the friction angle remains equal. Furthermore, the presence of vegetation reduces the erosion and improves the drainage in rainy areas (Hengchaovenich, 1998).

The study of soil reinforced with roots started in 1979 by Dr. Wu, who noticed an increase of shear resistance and safety factors of root-soil with cedar, Conium maculatum and Picea sitchensis doing large scale in situ direct shear test. In recent times other species have been investigated such as Populus tormentosa, Robinia pseudoacacia, Olea europaea and Chrysopogon zizanioides with direct shear and triaxial tests where all of them had an increase in cohesion. Furthermore, Chrysopogon zizanioides had a great performance due to their numerous roots (Wang & Wang, 2023).

The study of the effect of roots in the mechanical parameters of soils, a new term in the Mohr-coulomb equation, called apparent cohesion, Cr was introduced by Chock et al. 2015. This cohesion brought by the roots generates more area in the normal and shear stress graph, due to the cohesion generated by the roots which can be seen in figure 1.

$$\tau = c' + c_r + \sigma' \tan tan\,\theta'$$

where τ is the shear strength, C’ is the effective cohesion, σ’ is the effective normal stress and φ is the effective friction angle. The apparent cohesion or also called root cohesion can be obtained in three different ways, with the perpendicular root reinforcement developed by Wu et al. in 1979, with the available root density and tensile strength and with back analysis of failed slopes (Chock et al. 2015). Norris and Greenwood in 2006 determine that Cr can be expressed as:

$$C_r = 1.2T_r(A_r/A)$$

where Tr is the root tensile strength, Ar/A is the cross section of soil used by the roots, also known as root area ratio (RAR) (Gentile et al. 2010).

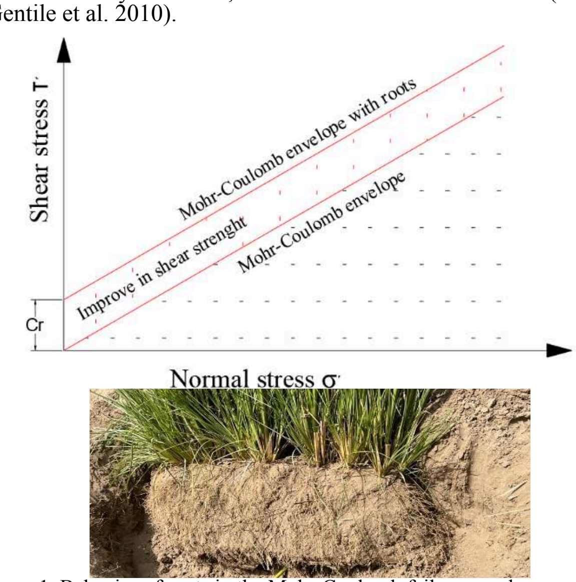


Figure 1. Behavior of roots in the Mohr-Coulomb failure envelope.

Chrysopogon zizanioides (figure 1), also known as Vetiver has a powerful root system made of numerous and thin roots that can go deep up to 4 meters, these roots have an average diameter of 0.66 ± 0.32 mm with a tensile strength of 85.1 ± 31.2 MPa. It also has a great resistance to metals like mercury, nickel, copper, and chromium as well as an acid soils, growing in soil with a pH between 3.3 and 9.5. (The Vetiver Network, 2008). In Peru, Vetiver only has been used hardly ever times, in the Bicentenario park, in Cantagallo, in San Juan de Miraflores and in Villa El Salvador.

Figure 2. Vetiver root matrix in sandy soil in Villa el Salvador, Lima, Peru.

Finite element analysis (FEA) is a numerical method developed in the 60´s to solve complex problems, it is based in a finite element model (FEM), which is made of interconnected elements called mesh, is critical to determine the soil properties, the boundary conditions and the solutions steps in the model to have accurate solutions.

Vetiver roots system in slopes have been modeled in finite elements model as a reinforced layer, to assess the factor of safety of the slope and compared with slopes with no reinforcement. Badhon, Islam & Islam (2021) modeled sandy slopes and added a top layer of soil 1 meter deep with cohesion that represents the root-soil vetiver zone which improve the factor of safety in 20.6%. Furthermore, Gentile & Elia (2010) recreate different cases including water and Vetiver, they concluded root-soil with Vetiver decreases the pore pressure as well as the factor of safety increases between 7% and 12%, however, when the soil has initial cohesion like clay, the improvement in the factor of safety is reduced.

The scope of this research is to analyze the incorporation of a matrix root-soil that variates the mechanical properties of a sandy soil top layer as well as the influence in the factor of safety. Different case scenarios were modeled in the finite element software Plaxis 2D changing the slope geometry and variating the presence of Vetiver soil and the depth of the top layer, on which the mechanical parameters were obtained by different authors.

2 METHODS.

In this investigation three different type of slopes were modeled in the software Plaxis 2D changing the geometry in each slope. The slope modeled was a cohesionless sandy slope covered with a soil reinforced layer. The mechanical parameters of the soil can be seen in the table 1.

Table 1. Properties of the soil modeled in Plaxis 2D.

Parameter	*Units*	*Plaxis Model*
Specific weight unsaturated	kN/m3	20
Specific weight saturated	kN/m3	18
Initial void ratio	-	0.65
Elastic modulus	kN/m2	50000
Poisson ratio	-	0.3
Effective cohesion	kPa	Variable
Effective friction angle	°	33

As well, the slope geometry changes with an inclination angle of 25°, 35° and 40° where the horizontal distance varies, and the vertical distance of the slope is 25 meters. Additionally, the depth of the root-soil matrix depends on the slope, being 3 meters deep for the slope of 25°, 2.5m deep for the slope of 35° and 2 meters deep for the slope of 40°. Furthermore table 2 and figure 2.

Table 2. Geometry of the slope modeled in Plaxis 2D.

Case study	*Inclination (°)*	*Depth root-soil matrix (m)*
Slope A	25	3
Slope B	35	2.5
Slope C	40	2

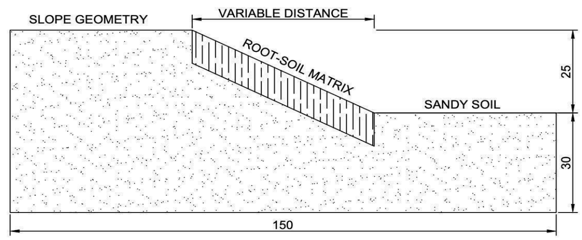


Figure 2. Slope geometry of the finite element model for each case study.

2.1 *Determination of mechanical parameters*

To obtain shear parameters of the root-soil matrix large data was reviewed by different authors. Most of the articles reviewed where sandy soils as the roots improve the cohesion of the sand particles. Few articles analyze on clayey soils, where the mechanical performance of the soil had a slight improvement in terms of stresses but no upgrading in cohesion. Table 2 reviews the most important and newer papers related to shear parameters improved with the matrix root-soil vetiver. Values of apparent cohesion (Vetiver cohesion improvement) are scattered between 2.5 and 60 kPa with no significant variation in the friction angle.

In this investigation, three values of cohesion were chosen to model the slope in finite elements models. Those cohesions are 6.8 kPa, 20 kPa and 60 kPa to effectively review all range of data obtained by the researchers from a low cohesion value obtained by Likitlersuan, to high cohesion obtained by Herrera & Amórtegui. Additionally, the factor of safety is compared in each cohesion to determine their behavior in the model.

2.2 *Finite element model*

To have an accurate development of the model in FEM, a Mohr coulomb soil model was chosen, as the parameters obtained are expressed in cohesion and friction angle. The soil is selected as drained, and the properties are mentioned in the table 1 shown previously. The mesh triangular elements were set with a coarsens very fine, with 1389 elements generated as well as 11379 nodes, the mesh generated can be seen in figure 3. The total length of the model is 150 m with a total height of 55 m.

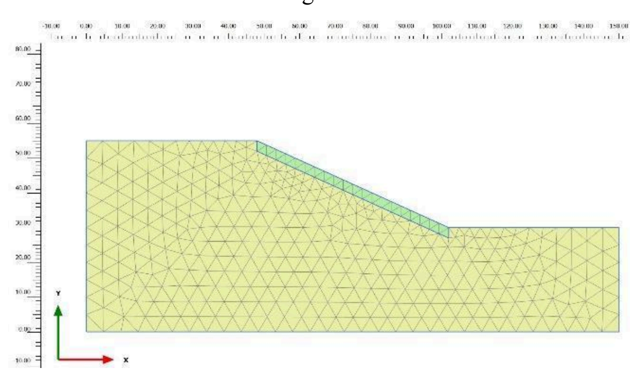


Figure 3. Mesh generated to case study for slope A.

To determine the factor of safety (FOS) of each case study slope, the software compute the phi-reduction method which reduces the initial mechanical parameters until failure. The loading type is an incremental multiplier of 0.1 reaching 100 steps until failure.

2.3 Factor of safety

It can be seen an increment in the FOS of the slopes with the addition of a matrix root-soil having higher values, even when the cohesion is not so great. This can be explained as the area won in

the Mohr Coulomb enveloped gained by the cohesion that now don't fail shown in figure 1. Additionally, the behavior of the different slopes is related which each factor of safety per slope as the cohesion increases, shown in figure 4. Also, the greater improvement is seen with the first addition of cohesion.

Table 3. Summary of the shear parameters in soils reinforced with vetiver.

Reference	Year	Type of soil	Cohesion (kPa)	Friction angle (°)	Root age (months)	Type of specimen
Mickovski, S., & van Beek, L.	2009	CM	2.5	34.5	6	Undisturbed
Likitlersuang et al	2015	SM	6.8	29.7	4	Undisturbed
Amiri, E., & Emami, H.	2019	SW	6.5	31.4	3	Undisturbed
Badhon, F., Islam, M., & Islam, M.	2021	SP	9.7	29.5	6	Undisturbed
Mahannopkul, K., Apiniti Jotisankasa	2018	SC	20	31.5	12	Undisturbed
Herrera, J., Amórtegui, J.	2017	SM	60	32	-	Undisturbed

Table 4. Summary of the models generated in Plaxis 2D.

Reference	*Case study*	*Index*	*Slope geometry (°)*	*Depth of root matrix (m)*	*Friction angle (°)*	*Cohesion (kPa)*	*Factor of safety*
Soil without roots	Slope A	A0	25	0	33	0	1.286
	Slope B	B0	35	0	33	0	0.794
	Slope C	C0	40	0	33	0	0.704
Likitlersuang et al.	Slope A	A1	25	3	33	6.8	1.444
	Slope B	B1	35	2.5	33	6.8	0.970
	Slope C	C1	40	2	33	6.8	0.813
Mahannopkul & Jotisankasa	Slope A	A2	25	3	33	20	1.497
	Slope B	B2	35	2.5	33	20	1.019
	Slope C	C2	40	2	33	20	0.835
Herrera & Amórtegui	Slope A	A3	25	3	33	60	1.582
	Slope B	B3	35	2.5	33	60	1.129
	Slope C	C3	40	2	33	60	0.955

3 RESULTS AND DISCUSSION

In total 12 models of finite elements were generated in the software Plaxis 2D so correlations between slope inclination, cohesion, factor of safety can be done. Greatly, the incorporation of a matrix root-soil in the slope improves the shear parameters which generates an increment in the final values of the factor of safety, as seen in table 4.

3.1 Cohesion vs factor of safety

When we associate those variables, it can be seen in each geometry case that was model (25, 35 and 40 degrees) the biggest improvement was when cohesion was added. When the cohesion value increment, the factor of safety also increased with almost a linear dependent behavior, in figure 4 these data can be observed.
Figure 4. Cohesion vs factor of safety in each slope.

When the cohesion changes from 0 to 6.8 kPa the improvement in the factor of safety is between 10% and 18%, being greater in the slope B (35° of inclination). After this, the improvement in cohesion reaches the peak value at 60 kPa, with an improvement in the factor of safety between 19% and 30% in comparison to a slope without a matrix root-soil vetiver. Additionally, table 5 shows how the FOS changes with the increment of the cohesion.

Figure 4. Factor of Safety (FOS) vs Cohesion (kPa).
Table 5. Improvements in FOS in each slope

Cohesion (kPa)	Slope A (25°)	*Slope B (35°)*	*Slope C (40°)*
6.8	10.94%	18.14%	13.41%
20	14.09%	22.08%	15.69%
60	18.71%	29.67%	26.28%

3.2 Slope inclination vs factor of safety.

It can be seen that the factor of safety decreases almost linearly depending on the slope inclination angle, as well as the cohesion parameter increases, the factor of safety shows the same behavior. Figure 5 shows how each author apparent cohesion brought by the root matrix exceed the soil without reinforcement behavior.

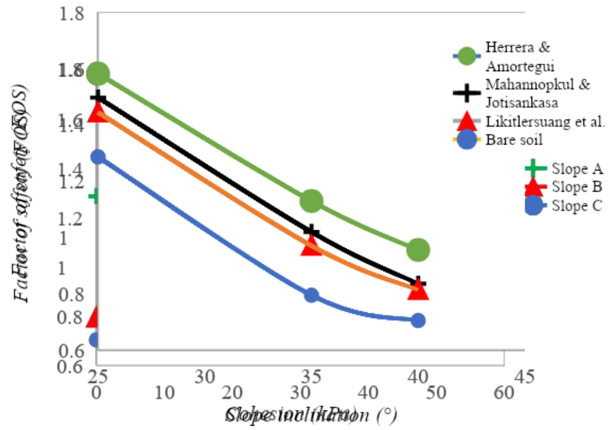


Figure 6. Factor of Safety (FOS) vs slope inclination (°).

3.3 Age root vs apparent cohesion.

Additionally, according to other authors there is a relationship between time growth of the vetiver soil with the improvement in apparent cohesion of the soil. All the data was graph, but not a clear relationship was found as shown in figure 6. It is important to mention that one of those soils was clay and that most of the parameters vary. In further investigation may add the root development through time in the value of how the cohesion improves. Furthermore, the growth time also can be linked with the RAR (root area ratio).

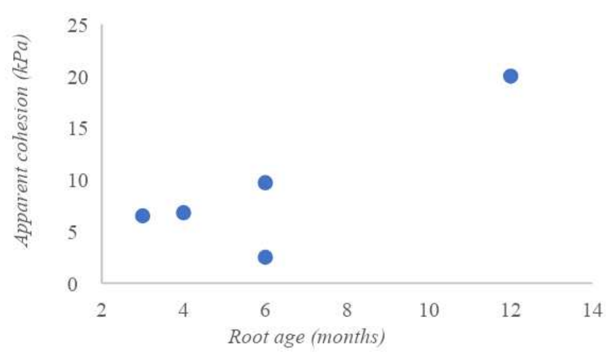


Figure 7. Root age vs apparent cohesion in articles found.

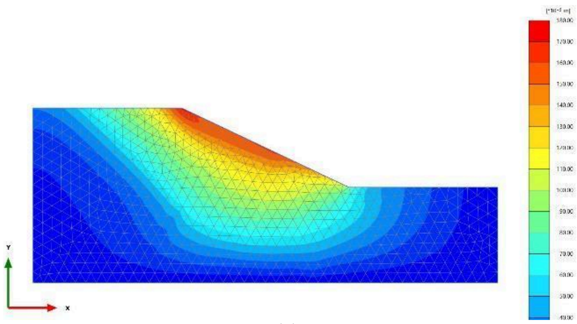
3.4 Displacements vs Slopes.

The maximum horizontal displacement generated in the slopes is when no root-soil matrix is considered, when it's added the displacement is reduced., in figure 7 the maximum displacement of Slope A with soil without vetiver can be seen as well as the failure envelope. Table 6 shows every displacement in each case study model where the behavior is particularly like the cohesion change, in the model the displacement is reduced almost linearly.

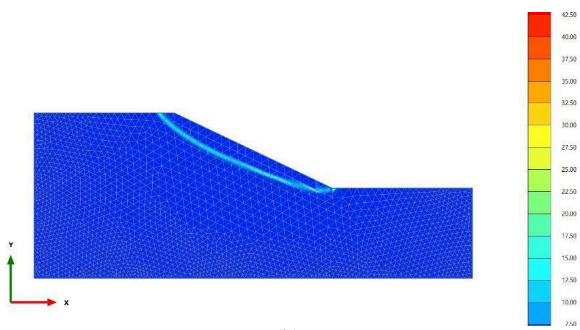
However, those displacement generated in this finite element model are greater values for stabilization due to the soil is highly deformable. Additionally, the change in geometry form slope A to C almost doubles the maximum deformations. It might be great to complement the investigation with other system of reinforcement to restrain the displacements in the FEM.

Table 6. Displacements in each slope model.

Cohesion (kPa)	Slope A (cm)	*Slope B (cm)*	*Slope C (cm)*
0	18	25	31
6.8	17.2	24.3	29.1
20	14.5	18.4	23.6
60	12.9	15.9	18.4



(a)



(b)

Figure 8. (a) Displacements in the slope A with bare soil. (b) Failure envelope of slope A with bare soil.

4 CONCLUSIONS

Rooted soil is an optimal solution to prevent superficial slope failure, specifically to soils without cohesion like sand. Roots penetrate the soil particles and generate an apparent cohesion that improves the shear parameters of the slope. Different authors researched and obtained cohesion values with a great range from 2.5 kPa to 60 kPa. Further investigations may complete this study on how time growth affects the RAR (root area ratio) and the cohesion of the matrix root-soil. With the 12 models generated, all the tests turned out with an improvement in the factor of safety.

The biggest impact in the factor of safety was when cohesion was added with a value of 6.8 kPa with a increment of 10% to 18%, from then, the improvement its slightly better in each case and its behavior is almost linearly dependent. In terms of deformations, the rooted soil brings a better stabilization which can be seen in how the deflection decreases almost linearly in each finite element model generated.

Finally, more investigation should be done to determine how the Vetiver behavior is in different soils and conditions like embankments. As well as how its growth is related or not to the improve in cohesion in each soil. Additionally, if any of other parameter is affected negatively in the soil by its inclusion. In this modelled case of study, there was an improvement, but other system might be used as well to reduce the maximum displacement.

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6 REFERENCES

Amiri, E., & Emami, H. (2019). Shear strength of an unsaturated loam soil as affected by vetiver and polyacrylamide. Soil & Tillage Research, 194, 104331. https://doi.org/10.1016/j.still.2019.104331

Badhon, F., & Islam, M. (2021). Contribution of Vetiver Root on the Improvement of Slope Stability. Indian Geotech Journal, 51(4), 829-840. https://doi.org/10.1007/s40098-021-00557-0

Chok, Y.H., Jaksa, M., Kaggwa, W., Griffiths, D. (2015). Assessing the influence of rootreinforcement on slope stability by finiteelements. Inernational Journal of Geo-Engineering, 6(12). https://doi.org/10.1186/s40703-015-0012-5

Darcy, H. (1856). Les fontaines publiques de la ville de Dijon. Dalmont, Paris.

Gentile, F., Elia, G., & Elia, R. (2010). Analysis of the stability of slopes reinforced by roots. WIT Transactions on Ecology and the Environment, 138, 189–200. https://doi.org/10.2495/DN100171

Gibson R., & Henkel, D. (1954). Influence of duration of tests at constant rate of strain on measured "drained" strength. Géotechnique, 9(1), 6-15.

Hengchaovenich, D. (1998). Vetiver grass for slope stabilization and erosion control. Pacific Rim Vetiver Network. https://www.vetiver.org/ICV3-Proceedings/THAI_slopestab.pdf

Herrera, J., & Amórtegui, J. (2017). Evaluación de parámetros de resistencia al corte en suelos de ladera cubiertos con vetiver. Revista de la Escuela Colombiana de Ingeniería, 108, 37-43. https://revistas.escuelaing.edu.co/index.php/reci/article/view/17/13

Likitlersuang, S., Lohwongwatana, B., Vanno, S., & Boonyananta, S. (2015). Laboratory and modelling investigation of root-reinforced system for slope stabilization. Soils and Foundations, 55(5), 1270-1281. https://doi.org/10.1016/j.sandf.2015.09.025

Mahannopkul, K., Jotisankasa, A. (2019). Influences of root concentration and suction on Chrysopogon zizanioides reinforcement of soil. Soils and Foundations, 59, 500-516. https://doi.org/10.1016/j.sandf.2018.12.014

Mickovski, S., & van Beek, L. (2009). Root morphology and effects on soil reinforcement and slope stability of young vetiver (Vetiveria zizanioides) plants grown in semi-arid climate. Plant and Soil, 324, 43-56. 10.1007/s11104-009-0130-y

Norris, J., & Greenwood, J. (2016). Assessing the role of vegetation on soil slopes in urban áreas. The Geological Society of London. 157(4). https://media.geolsoc.org.uk/iaeg2006/PAPERS/IAEG_744.PDF

Terzaghi K. 1936. The shearing resistance of saturated soils. Proc. 1st Int. Conf. Soil Mech., Cambridge, Mass.

Wu T., McKinnel, W., & Swanston, D. (1979). Strengh of Tree Roots and Landslides on Prince of Wales Island Alaska. Canadian Geotechnical Journal, 16(1), 19-33. https://doi.org/10.1139/t79-003

Terzaghi K. 1936. The shearing resistance of saturated soils. Proc. 1st Int. Conf. Soil Mech., Cambridge, Mass

The Vetiver Network International. (2008). Aplicaciones del sistema vetiver Manual técnico de referencia. https://www.vetiver.org/TVN_manual_spanish%20o.pdf

Wang, B., Wang,S. (2023). Shear Strength Analysis and Slope Stability Study of Straight Root Herbaceous Root Soil Composite. Applied Sciences. 13 (23). https://doi.org/10.3390/app13231