Assessing the effects of vetiver grass on slope stability using Finite Element Analysis.

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Abstract

Vegetation has a good influence on stability of slopes due to its root cohesion that provides additional strength to the soil layer and its hydrological effect involving evapo-transpiration which leads to increase in soil suction and reduction in pore water pressure, consequently increasing the effective soil strength. Vetiveria zizanioides or vetiver grass, one of the famous slope stabilizing plants, has extensively been used in many tropical and subtropical countries. Quantitative studies of how much contribution the grass really provides towards slope stabilization are relatively scarce having focus on engineering methods which are relatively costly and with no ecological benefit.

With the aim of investigating the mechanical behavior of grass stabilized slope, the properties of vetiver grass have been determined from laboratory experiments and incorporated in the nonlinear Finite Element model using PLAXIS 2D software. The parametric studies on different ground types, slope geometric conditions and spatial distribution of vetiver grass confirmed that the effect of the grass is higher on soils of lower cohesion and steeper inclination. It has also been found out that better improvements can be achieved when the grass extends beyond the toe, in excess of the slope face.

Key words: Vetivergrass, Vetiveria zizanioides, slope stability, PLAXIS 2D, parametric study

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Introduction

Vetiver grass is a perennial grass that had been promoted to help conserve the soil and runoff by the World Bank in 1980's. It has been developed to become an important soil bio engineering method (Grimshaw, 1994; Greenfield, 1998). Vetiver grass is a kind of vegetation that is very fast growing and requires low maintenance. The length of vetiver roots was observed to grow up to 2.0-3.5 m (Chinapan et al., 1997).

Ke et al. (2003) tested vetiver on several test sites and got promising results for the use of the plant as a bank protection measure. Verhagen et al. (2008) also conducted different laboratory and model tests on vetiver grass to realize its use in coastal areas and showed that vetiver grass is able to establish a full stop of band erosion caused by rapid draw down.

Jiru and Wari (2019) reviewed the role of vetiver grass for soil and water conservation in Ethiopia. According to their reports, it was introduced to Ethiopia since 1970 to prevent invasion of couch grass in the coffee production area and later for soil and water conservation purposes.

Even though there is a wide range of application of Vetiveria zizanioides in many tropical and subtropical countries (Truong et al., 2008), there is a gap in the level of safety provision about the contribution of the grass towards slope stabilization. This study aims at studying and modeling the effect of vetiver grass on stability of different slopes. The influences of slope geometry and property of underlying soil on the extent of slope stabilization with vetiver grass root are core areas of this research.

Parameterizing the mechanical properties of vetiver grass

Root systems mechanically reinforce soil by transferring shear stress in the soil to tensile resistance in the roots (Fitter 1993), In addition it is asserted that the root architecture, especially the branching pattern has a close relationship with the strength of anchorage (Stokes et al. 1996).The extent of mechanical stabilization of vegetation for slope stability depends on depth of root zone, the root area ratio and root reinforcement.

Depth of root zone is the effective distance beyond which plant roots cause little or no effects on the soil shear strength, which can be determined based on previous experiences (Chinapan et al. 1997).

Root area ratio is the fraction of the total cross-sectional area of a soil that is occupied by roots (Gray and Sotir1996). For the same specimen height, the root area ratio, $[\frac{AR}{A}]$, is equal to the ratio of volume of root and volume of soil.

$$[\frac{AR}{A}]=V_r/V_s=\rho_s m_r/\rho_r m_s \quad \text{..... (1)}$$

where: ρ_r = density of root
ρ_s = density of soil
m_r = mass of root
m_s = mass of soil

With the corresponding unit weights being determined from the laboratory tests, and mass ratio between soil and root is found to be 0.0012, also from laboratory test, the root area ratio has been determined to be:

$$([\frac{AR}{A}]) = 17.1/9.54 * 0.0012= 0.0021$$

Root reinforcement is the term used to express the additional shear strength provided by vetiver grass on the soil. It is quantitatively expressed using the "soil cohesion due to root reinforcement", or "root cohesion". Root cohesion can be determined using the root reinforcement model of Wu et al. (1979), which assumes that the increased soil shear strength can be expressed as an additional cohesion, C_r, calculated as:

$$C_r= 1.2 * T_r \quad \text{..... (2)}$$

and $$T_r= t_R*[\frac{AR}{A}] \quad \text{..... (3)}$$

where: T_r = the total tensile root thread strength per unit area of soil,

t_R = mobilized root tensile stress.

Tensile strength test was conducted at the Ethiopian Conformity Assessment Enterprise laboratory on 20 vetiver grass roots of 20 cm length and 1-2 mm diameter, collected randomly from Debrezeyt agricultural research center. The mean values of the tensile force (t_R), elongation and tensile strength are thus calculated to be 40.8 N, 23.74mm and 23.7 MPa respectively.

The total tensile root thread strength per unit area of soil was determined to be:-

$T_r = t_R * [\frac{AR}{A}] = 23.7 * 0.0021 = 0.05$ MPa

$C_r = 1.2 * T_r = 1.2 * 0.05 = 0.06$MPa = 60 kPa

Wu et al. (1979) assumed that all the roots attain their maximum strength at the same time. But practically, the maximum load that the bundle of root fibers could resist is less than the sum of each of their individual strengths because roots break at different instant depending on the way the load is distributed by all the fibers (Pollen and Simon 2005). Since the Wu et al. (1979) model also does not consider pulling out of root from soil, it over estimates the root cohesion value. To account for this limitation of the root reinforcement model, only 25% of additional root cohesion is added to the soil cohesion for this study. Therefore additional cohesion attained from the root reinforcement is taken to be 15 kPa.

Parametric studies

With the aim of determining the effects of vetiver grass on slopes of different soil types which are prone to failure, Finite Element Analysis have been performed by varying the geometric inputs of the FE model. The root was assumed to propagate 2m below the slope surface since the length of vetiver roots was observed to grow up to 2.0-3.5 m Chinapan et al.(1997) the minimum length is taken. This 2m layer of soil is taken to be the zone of additional cohesion from root reinforcement. Four different types of soils were considered; namely loose sand, soft clay, medium stiff clay, and stiff clay soil whose properties are presented in Table 1, have been adopted from Bowles (1997) and Garg S.K (2014).

Table 1 soil properties used in the analysis

Parameter	Symbol	Unit	Loose sand	Soft clay	Medium stiff clay	Stiff clay
Soil unit weight above phreatic level	$\gamma_{unsaturated}$	kN/m^3	14.5	13	15	17
Soil unit weight below phreatic level	$\gamma_{saturated}$	kN/m^3	18.85	18.2	19.58	20.57
Horizontal permeability	K_x	m/day	0.5	1.00E-09	1.00E-11	1.00E-11
Vertical permeability	K_y	m/day	0.5	1.00E-09	1.00E-11	1.00E-11
Young's modulus	E_{ref}	kN/m^3	25,000.00	7,469.00	15,000.00	25,559.00
Poisson's ratio	v	-	0.25	0.38	0.33	0.3
Cohesion	c'	kN/m^2	1	10	25	50
Friction angle	Φ'	^{o}	30	17.5	19	20
Dilatancy angle	ψ	^{o}	0	0	0	0

Two different scenarios were studied in terms of slope height. In the first case, slope height which gives a stable slope with FOS of around 1.5 is calculated for all soil types.

To calculate the stable height, Taylor's stability chart is used to start with and the exact height is determined by trial and error, using PLAXIS 2D software. Consequently, four different slope heights were determined for the four different soil types as presented in Table 2. The stable height is needed because the grass takes at least 4 - 6 months to develop fully so that the slopes have to stay stable during that period.

Table 2 computed slope heights for different soil types

Soil type	Slope height (m)
Sand	1
Soft clay	4.9
Medium stiff clay	13.5
Stiff clay	21

The second case was developed considering the same slope height for all slopes, in order to do make a more accurate comparison of the effect that the grass provides for slopes with different soil types. A height giving stable loose sand slope (H=1m) is used for this case and all slopes were modeled using this height because it is the smallest and gives a stable slope for all soil types. To study the effect of slope angle, two different slope angles, 45^{o} (1V: 1H) and 26.6^{o} (1V:2H) have been considered. The effect of the grass when it covers the slope face only and when it extends beyond the toe of the slope was also examined. Figure 1 shows the finite element model.

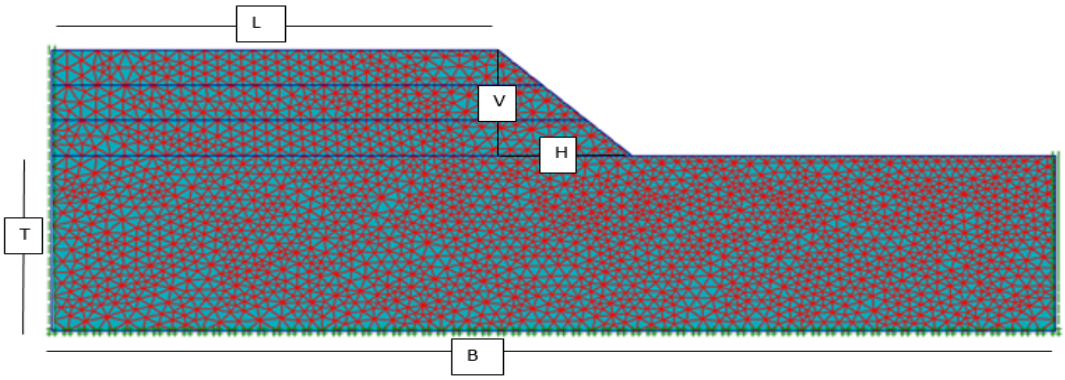


Figure 1 Finite element model.

Table 3 Geometric parameters used for the analyses

Slope	Soil type	L(m)	V(m)	H(m)	B(m)	T(m)
1:1 slope with a slope height of 1m	loose sand	40	1	1	61	20
	soft clay	40	1	1	61	20
	medium stiff clay	40	1	1	61	20
	stiff clay	40	1	1	61	20
1:1 slope with slope different slope height	loose sand	40	1	1	61	20
	soft clay	40	4.9	4.9	64.9	20
	medium stiff clay	40	13.5	13.5	73.5	20
	stiff clay	40	21	21	81	20
1:2 slope with different slope height	loose sand	40	1	2	62	20
	soft clay	40	4.9	9.8	69.8	20
	medium stiff clay	40	13.5	27	87	20
	stiff clay	40	21	42	102	20

Discussion of results

The effects of vetiver grass on slope stability were analyzed by considering factor of safety (FOS) and percentage increase in FOS. The method used to calculate the factor of safety is the Phi-c reduction method implemented in the PLAXIS software in which, PLAXIS reduces the parameters tanΦ and c until failure of the soil occurs, during the calculation process.

Table 4 summarizes the factor of safety values obtained from the finite element analysis computations for different types of ground conditions when the grass extends to different levels beyond the slope face, as compared to that without grass, by considering a similar slope height of 1 m in all cases, so as to avoid the effect of height on the factor of safety.

Table 4. FOSs and percentage increase in FOSs for different spatial arrangement of vetiver grass with 1m slope heights

Soil type	FOS without grass	FOS and % increase in FOS with grass extends to									
		slope face only		1m beyond slope toe		5m beyond slope toe		10m beyond slope toe		model end (20m beyond toe)	
		FOS	% incr. FOS	FOS	% incr. FOS	FOS	% incr. FOS	FOS	% incr. FOS	FOS	% incr. FOS
Loose sand	1.55	3.58	131	4.6	197	4.6	198	4.63	199	4.7	203
soft clay	5.57	7.31	31.3	7.8	40	8.1	49	8.46	52	8.52	53
Medium stiff clay	10.81	12.2	12.4	13.3	23	13.5	25	13.7	26	14.3	32
Stiff clay	19.09	19.6	2.44	19.7	3.1	19.9	4.4	20.2	5.6	20.4	6.7

The contribution of the vetiver grass is evident from Table 4 and the increase in FOS with increasing soil cohesion and area covered by the grass is something one can expect. Since the percentage increase in the FOS is higher for soil with very low cohesion, its application is appreciated in such type of ground conditions. It can also be observed that extending the grass very far away from the slope toe cannot produce significant enhancement in the slope protection. The extent of covering the ground beyond the slope toe can be facilitated by the plots in Figure 2, in which the FOS achieved is presented against the distance covered by vetiver grass.

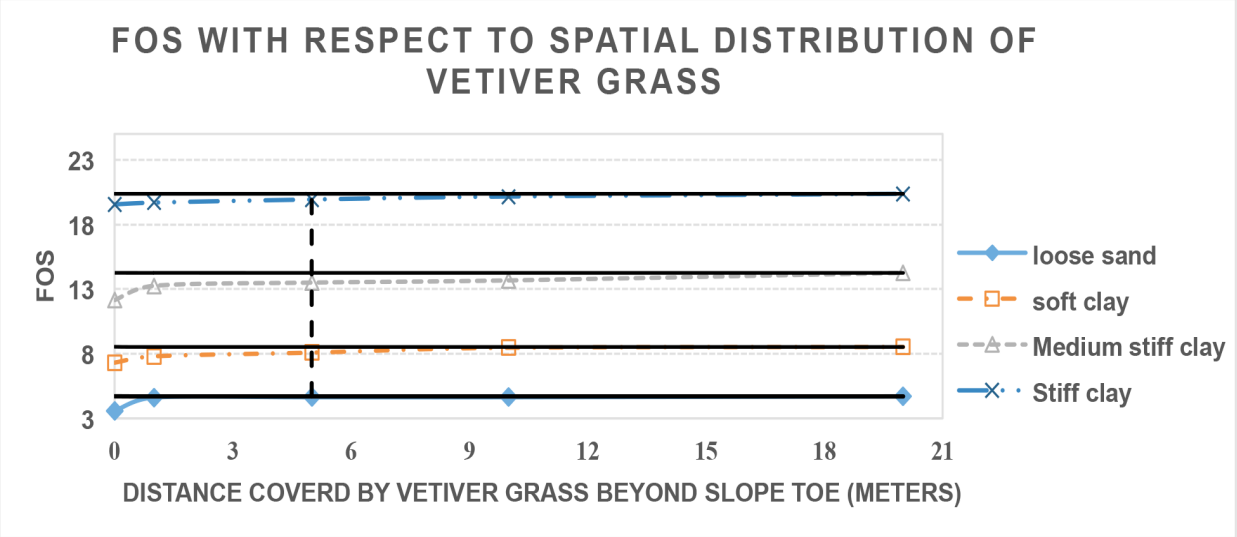


Figure 2 FOS vs. spatial distribution of vetiver grass.

Although the FOS increment is pronounced for the soil types with lower cohesion, the ground improvement seems to be effective only up to a certain distance beyond slope toe, in all the soil types under consideration. The convenient optimum distance beyond the toe after which the slope factor of safety remains constant is found to be 5m.

The other series of computations have been performed by using the stable slope heights determined earlier (Table 2) and keeping two cases of slope angles, and considering the two extreme cases of extending the grass beyond the toe. The summarized FOSs and percentage increases in FOSs are presented in Table 5.

Table 5. FOSs and increase in FOSs for soils with different slope heights

Soil type	Slope height (m)	FOS without grass		FOS and increase in FOS with grass at slope face				FOS and increase in FOS with grass extending 20m beyond toe			
				1V:2H		1V:1H		1V:2H		1V:1H	
		1V:2H	1V:1H	FOS	% Incr. FOS	FOS	% Incr. FOS	FOS	% Incr. FOS	FOS	% Incr. FOS
Loose sand	1	2.19	1.55	4.17	90	3.58	131	5.68	166	4.7	203
Soft clay	4.9	2.11	1.59	2.14	12	1.82	14	2.32	9.7	1.97	23.6
Medium stiff clay	13.5	2.23	1.53	2.25	0.8	1.59	4.4	2.28	1.96	1.72	12.7
Stiff clay	21	1.98	1.57	1.99	0.2	1.58	0.6	1.99	0.7	1.59	1.23

The previous observation of decrement of the % increase in FOS with increase in soil cohesion is evident in Table 5. The expected effects of slope steepening can also be clearly seen from the summarized results. The FOS improvement is high for slope of V: H 1:1 because of its shallow critical slip surface covering relatively larger portion of the root zone. The sleep surfaces

of the two cases of stabilized and unstabilized slope are depicted in Figure 3.

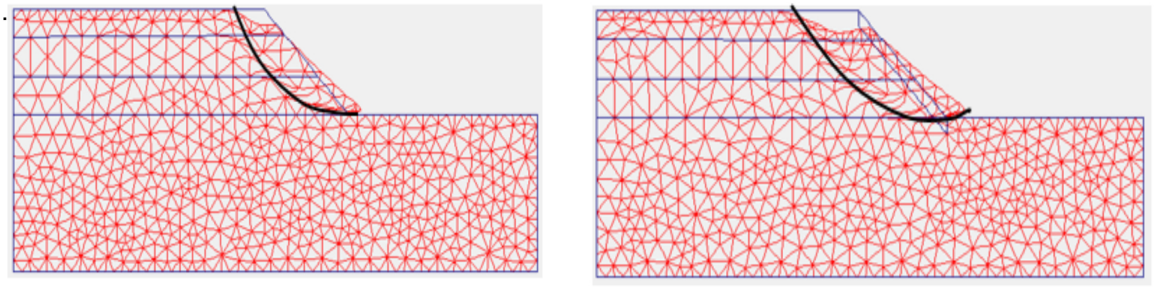


Figure 3.Sliding mass for slope with and without vetiver grass, respectively.

The critical slip surface develops along a soil layer beneath root zone as this soil layer is the top of the weak zone of the slope after introducing root reinforcement within the root zone. In addition to that, to mobilize additional cohesion from root reinforcement within the root zone, the sliding mass has to increase and this is achieved by increasing the depth of critical slip surface. Chok et al (2015) found similar result in terms of critical slip surface location with the presence of vegetation. As the slope is reinforced with vegetation, the critical slip surface goes deeper and shallow planar slide will no longer be critical.

Conclusions

The Finite Element Analysis results conducted by considering different soil types stabilized by vetiver grass, whose mechanical behavior were determined from laboratory experiments, showed its advantages against destabilizing agents such as rain fall and surcharge in addition to preventing soil erosion. The improvement of FOS is not only governed by root cohesion and depth of root zone but is also dependent on underlying soil property, slope geometry and spatial distribution of the grass. It was found out that the improvement is pronounced for soils with smaller cohesion than those with higher strength and stiffness. The stabilization is also found to be better for steeper slopes which are prone to shallow land slide and erosion problems. To achieve safe and more economical results, the grass should extend only 5m beyond the slope toe. The presence of vetiver grass root increases the depth of critical slip surface, requiring higher external force to slide the mass within the critical slip surface. Thus, shallow land slide problem will no longer be critical for slopes with vetiver grass.

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