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Stability Evaluation of Reinforced Slope Soil with Vetiver Grass against Erosion and Landslides Hazards by Using Finite Element Method

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This work studied slopes with different geometric situations. The purpose is to select types of soil for embankment construction to stabilise the site by using nearby accessible filling materials. Then, PLAXIS-2D software was used including five (6) phases of sequential calculation such as soil, structure, mesh generation, conditions of flow and construction stage and the use of Vetiver grass for embakment stability reinforcement. Choices were made on soil properties, loading, water table effect, embankment geometry and reinforcement actions of vetiver grass. The method is based on using diverse filling materials and varied slope gradients with different heights. So, the slope analyse involves homogeneous soils, in addition to slope section by various soils strata. Results obtained showed that the increase in soil shear strength is related to the mechanical effects of vetiver roots and make the soil able to resist shear stress due to the presence of roots density within the soil mass and the root tensile strength. It is also noticed that the soil suction effects and roots reinforcement increased the apparent cohesion of the soil, showing an important role played by vetiver grass in stabilising shallow-seated slopes failure with significant effect on slopes stability.

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Keywords: Slope analyse; embankment; filling material; vetiver; roots.

1. INTRODUCTION

Embankment adversity is often observed in Congo republic largely in the northern region of Brazzaville City. Buildings are overcome by slope uncertainty every year during the rainy seasons. Approximately 70% of the total precipitation in Brazzaville City occurs in rainy seasons. Thus, slope instability occurrence carries the major risk in this rainy period [1]. The manmade slope accompanied by vegetation loss of slight soil located on abrupt slopes is also the reason of slope instability as well. Among all the reparations caused by slope instability in Brazzaville City, 45% of losses remains in elevation areas [2].

Slope can be made by nature and also by man. It can be seen as embankment and cuttings. In slope study, any slope instability constitutes a challenge in recent years. Slope instability can involve various factors in its existence. Including natural slopes as well as failure when it is governed by geometry changeability, acting forces and shear resistance decrease. Huge mass of soil in inclined site evidently can conduct to sliding [3-6]. Therefore, shear strains in soil larger than equivalent soil shear strength. Thus in the specific slope analyse it is significant to consider how the shear parameters of various filling materials affect the embankment instability. In the same way to identify the nearby existing behaviour of filling material once it is used in embankment construction [7]. Plaxis-2D is useful for this type of study. In general parameters as water pressure, existence of ruthless feature of shallow soil, subsoil, ground behaviour are ignored by simplified methods [8]. Then once it derives from finite element code latest studies consider that Finite Element Method founded on computational checks are giving better outcomes including earthquake study [8-12]. Finite Element Method also gives precise findings with comparison to additional tools [13-15]. Therefore, the current study is performed by using Plaxis 2D software.

The slope stability analyse often needs reinforcement actions such as the use of vegetation to reinforce its stability against disastrous phenomena such as landslides or collapse. The vegetation effects on slopes stability are well known. Vegetation effects on slope stability conduct to modify of the soil water regime, which affects the suction or pore pressure in soil. Moreover, vegetation can increase the slope stability by root reinforcement. Wu et al. [16] studied the slopes stability before and after forest cover elimination and determined the importance of shear resistance of tree roots on the slopes stability. This study showed that vegetation is able to contribute in increasing slopes shear strength through reinforcement of roots. Wu et al. [16] indicated that the slope failure is occurred when the vegetation effects were not considered in analyses of slope stability.

It is indispensable to recognise that natural slopes stability is affected by characteristic changes in the soil and vegetation. It is questionable that the original soil profiles of natural slopes are absolutely unvarying or regular. Even inside an identical soil layer, soil properties have tendency to differ from point to point [17]. The vegetation evolution is subtle to environmental changes. Naturally, different kinds of vegetation are propagated on a natural slope, for example a mixture of grasses, scrubs, trees and herbs. The difference in their size and physical properties will have an influence on the slope stability. Then, using a single input value for the dependent parameters of vegetation in the slopes analyse consists in an initial approximation of the field environments.

This work is focused on embankment construction by using accessible local materials and the effects of vegetation on slopes stability using the finite element code. The finite element code has a facility to carry out the embankment construction and extent the vegetation effects where slope geometry is discretised into small elements. Considering this work objectives, only the root reinforcement effects are included in the analysis of slope stability without considering the changes in vegetation and soil properties as well.

2. STUDY AREA

The embankment site is located in the southern part of Brazzaville City, in Mfilou district as shown in Fig. 1. Its relief presents flats areas, valleys and hilly zones as well. The existing studies showed that the years 80's have been less warm than the years 90's, where the recent temperatures evolution in Congo before 1970 and after is categorised basically by two episodes. The net temperature variation from 1932 to 2010 indicates an increase in average temperatures of +0.5ºC to 1ºC in the earlier two decades. Whereas, the maximum and minimum average temperatures in the 1990 s increased during the two recent decades. The maximum and minimum altitudes observed are 1100 m and 360 m respectively. The study area has a tropical climate with a rainy season from October to May, and dry seasons between January-February and June-September. The annual fluctuation of rainfall is among 1250 mm and 1350 mm/year [18]. The hydrogeology is part of the Bateke's water table, with an area of 270 km^2. The aquifer composition is made of sandstone which with a few contributions in the groundwater mineralogy. Two hydro chemical areas are well defined from the use of $Ca^{2+/}Mg^{2+}$ ratio. The first zone contains the calcium minerals which are important for weathering process and the second one with a higher ratio of Ca2+/Mg2+ presents the dissolution of magnesium [19]. The soils repose on sedimentary series from the base to the top such as series of Inkisi sandstone, series of Stanley Pool sandstone and series of Bateke's plateau. Generally, these soils contain a very low clay content [20,21]. The Central Basin represents the intracratonic depression of Central Africa with sediments accumulation, tectonic activity and erosion process for a long history. The geological contextual is based on Precambrian to Paleozoic age formation as a support for a Mesozoic to Cenozoic sedimentary cover which rests unconformably on a Precambrian basement. Whereas, the Precambrian to Paleozoic basement is observed downstream from the Stanley Pool where the sedimentary cover is formed by sandy materials outcropping upstream from the Stanley-Pool's series [22].

3. MATERIALS AND METHODS

3.1 Slope Model

We considered Embankment height as 7 m, 12 m and 17 m. Various parameters of slope were used such as 1.5H:1V, 2H:1V, 2.5H:1V. 3.5 m of Embankment top width. 15-nod elements of plain strain were considered for the slope Analysis. Likewise Scheme properties (x_{min}, x_{max}, y_{min}, y_{max}) fluctuates according to Height and Embankment slope as it was considered in the current research work. Coarseness factor of Mesh generation is used such as medium. The layer real height under the embankment height is 3.5 m and slope geometry model was created by using Finite Element Method as shown in Fig. 2.

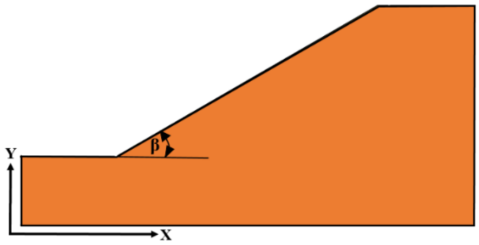

Fig. 1. Embankment model for analysis

Various accessibility filling materials were used for the study and modelling by using soil model of Mohr-coulomb. Every filling material was used as the homogenous filling material. Likewise for additional situation two filling materials layers with 3.5 m base as unique filling material and lasting height one filling material. Various filling materials used in the current study are registered in Table 1.

3.1.1 Mesh generation

The Gl obal coarseness is assumed as medium for generating Mesh (Fig. 2).

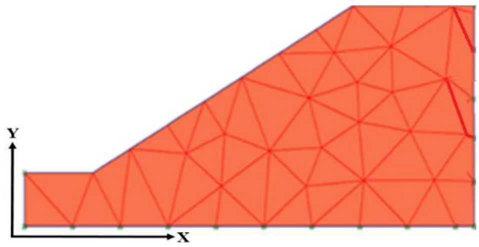

Fig. 2. Mesh generation

Before calculation procedure, it is essential to produce initial stress from Jacky's formula (Ko =1-sinφ). In this stage, the whole Embankment study is approved and safety factor can be determined.

3.2 Analysis of Roots Reinforcement

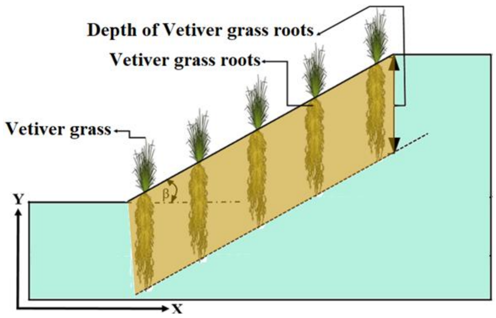

Fig. 3. Root reinforcement model

The plant roots capacity to reinforce a soil mass stability is well recognised. The presence of plant roots with great tensile resistance increases the confining pressure in the soil by its strictly spaced matrix system of roots. The soil is guaranteed together by the effect of plant roots which increases its shear resistance. Wu et al., [16] indicated that the root reinforcement of shear strength contributes to increase in characteristics of cohesion. Wu et al. [16] suggested an easy perpendicular model of root to evaluate the increase in shear strength of soil because of root reinforcement. The increase in shear resistance of the soil (Sr), is expressed as follow:

$$S_r = t_R\,(\cos\theta \tan\varphi' + \sin\theta) \qquad (1)$$

Where Sr = shear resistance increase from root reinforcement, t_R = average tensile resistance of root per unit area of soil, θ = shear rotation angle, and φ′ = angle of friction.

Then, the plant roots mechanical effect increases the soil mass cohesion, Sr is considered as apparent soil cohesion, recognised as apparent cohesion of root (c_R). Characteristic values of apparent cohesion of root (c_R) varies from 1kPa to 17.5 k Pa [23]. These cohesion values were found from several studies using different techniques with back analysis as well, direct shear tests, information about root density combined with equations of vertical root model, and back analysis combined with information about density root. The values of apparent cohesion of root (c_R) depend on the kind of vegetation including in-situ soil environments (Fig. 3).

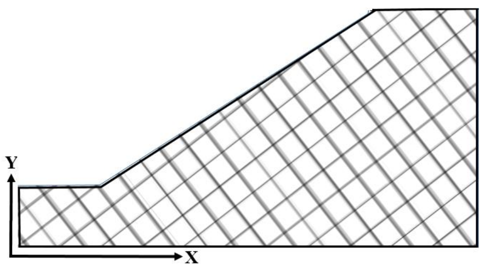

Fig. 4. Deformed Mesh at Failure for the Slope with c′=0

3.3 Slope Stability Analyses

Wu et al. [16] combined the vegetation effects with slope stability analysis using limit equilibrium approach. In limit equilibrium approaches, the soil shear resistance alongside a potential sliding surface is supposed to be completely mobilised at the failure point. The equation of Mohr-Coulomb was used to define the soil shear strength:

$$\tau = c' + (\sigma - u)\tan\varphi' \qquad (2)$$

By including the root reinforcement effect, Equation (2) becomes:

$$\tau = (c' + c_R) + (\sigma - u)\tan\varphi' \qquad (3)$$

Wu et al. [16] combined the apparent cohesion of root (c_R) in their analysis of infinite slope and met an increase in the safety factor (FS) for some slopes. The findings showed that plant roots enhanced the forested slopes stability. But, there was no enough published works using numerical interpretations to evaluate effects of root reinforcement. This work uses numerical analysis which permits preventing the root zone extent. By assigning different values of apparent cohesion of root (c_R) to the root zone, its implication on the safety factor is assessed.

3.4 Numerical Analysis Using Vegetation (Vetiver Grass) Effects Model

The vegetation effect on the slopes stability was studied using the finite element code. The discretisation process of the finite element approach breaks down the geometric slope into insignificant elements facilitating the integration of the veetiver effects in the analysis of slope stability. Vegetation effects are considered in the analysis of slope stability by adapting the soil properties of the discrete soil element that is affected by vetiver grass vegetation. Such as, a higher value of soil cohesion can be observed in the slope top layer because of the supplementary apparent cohesion from root presence. Change in soil suction produced by vetiver grass vegetation can as well be merged in the finite element study. The suppleness in finding the vegetation-affected components means that the variable and random aspect of vegetation can be analysed efficiently by modelling. This is limited to the root reinforcement effects on the slopes stability analyse.

3.5 The Finite Element Model

The finite element model used in this work adopts 2-dimensional plane stress conditions by using Plaxis 2D and considering elasto-plastic model and Mohr-Coulomb failure criterion. The software calculates the slope safety factor (FS), attached to an unexpected increase in nodal displacements as a signal of rupture conditions [10]. In the current study, the soil properties are shown in Table Two surplus vegetation-dependent parameters used in the analysis of slope stability are apparent cohesion of root (c_R) and root zone depth (h_R). Apparent cohesion of root (c_R) is considered as the apparent cohesion of soil produced by the system of vetiver root matrix. The root zone depth (h_R) is defined as the effective space beyond which vetiver roots cause few or no effects on the soil shear resistance. Then, two scenarios can be considered: (1) Vetiver grass limited to the slope surface only; and (2) vetiver grasss spreading over the full ground surface. Parametric studies are carried out to evaluate the slope stability sensitivity to the change in Vetiver-dependent parameters.

4. RESULTS AND DISCUSSION

The analysis of homogeneous embankment for 7 m Height can be seen from Table 2.

Table 2 and Fig. 5 show that the highest safety factor values are beyond 3.0 regardless the soil type and the homogeneous embankment slope of 7 m, excluding for embankment with filling material 1 and slope 1.5H: 1V. The minimum safety factor value is 1.72 which means the embankments erected with homogeneous soils are consistent in the short term circumstances. Embankment constructed with filling material 3 showed the most stability and safety.

4.1 Homogeneous Embankment Analysis Once Height = 17 m

Since the Table 3 and Fig. 6 all values of safety factor are superior to 1.5 regardless the soil type and homogeneous embankment slope of 7 m. The lowest value is 1.56. The difference between safety factors is the same comparable to height embankment of 7 m.

4.2 Homogeneous Embankment Analysis Once Height = 17 m

All the safety factor values observed in Table 4 and Fig. 7 are superior to 1.5 regardless the soil type and homogeneous embankment slope. The lowest value remains 1.51. The difference among safety factors remains the same which previously perceived above. Less distance can be noticed among curves.

Table 1. Properties of filling materials

Parameters	Filling material1	Filling material 2	Filling material 3
γ_{sat} (KN/m$^{3)}$	18.50	21.50	19.50
γ_d (KN/m$^{3)}$	15.50	19	17
E (MPa)	80	250	150
υ	0.3	0.3	0.33
C (kPa)	5	35	18
φ (^{o})	32	10	32

Table 2. Homogeneous embankment for different filling matrials and slopes (H=7 m)

Slope	Filling material 1	Filling matrial 2	Filling matrial3
1.5H:1V	1.72	2.70	2.82
2H:1V	2.09	2.91	3.27
2.5H:1V	2.41	3.13	3.69

Table 3. Homogeneous embankment considering various filling materials and slopes (12 m)

Slope	Filling material1	Filling material 2	Filling material 3
1.5H:1V	1.56	2.42	2.60
2H:1V	1.95	2.34	2.93
2.5H:1V	2.30	2.51	3.37

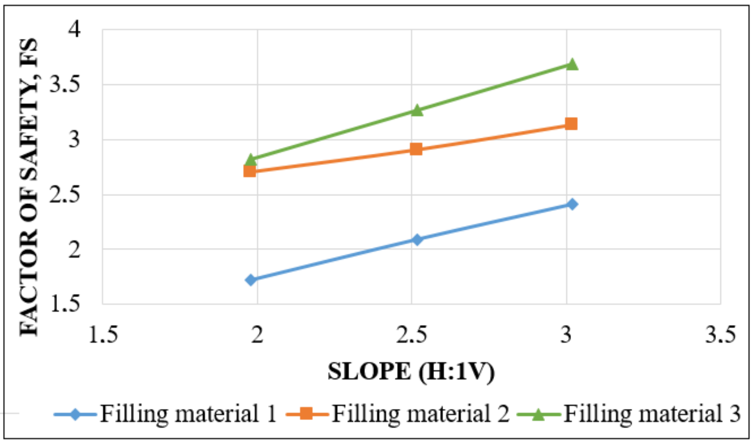

Fig. 5. Slope vs safety factor considering 7 m embankment and varied filling soils

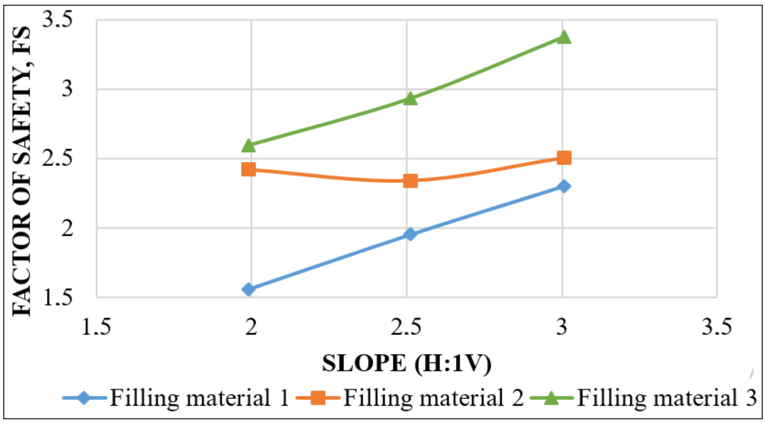

Fig. 6. Slope vs safety factor for embankment and varied filling soils (12 m)

Table 4. Homogeneous embankment and varied filling materials and slopes (H= 17 m)

Slope	Filling material1	Filling material 2	Filling material 3
1.5H:1V	1.51	1.77	2.41
2H:1V	1.93	2.07	2.96
2.5H:1V	2.42	2.36	3.46

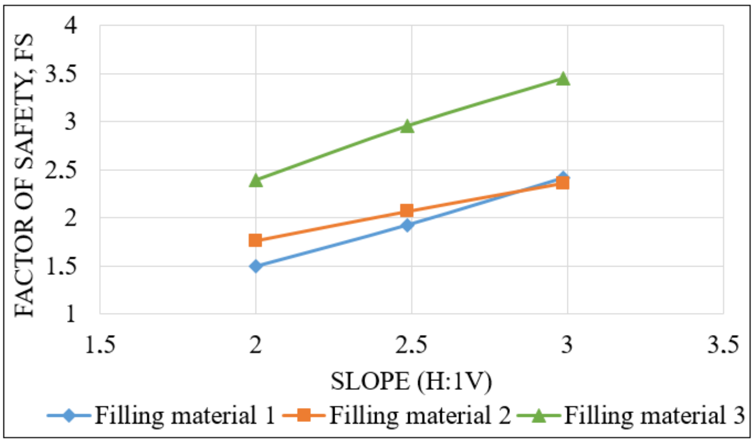

Fig. 7. Slope vs safety factor once embankment has different filling materials and 17 m height

4.3 Embankment Analysis Using Two Filling Layers Once Height= 7 m

Table 5. Embankment and varied filling materials and slopes (H=7 m)

Slope	Filling material1+ Filling material 2	Filling material 1+ Filling material 3	Filling material 2+ Filling material 3
1.5H:1V	1.81	2.35	2.87
2H:1V	2.19	2.71	3.15
2.5H:1V	2.64	3.07	3.42

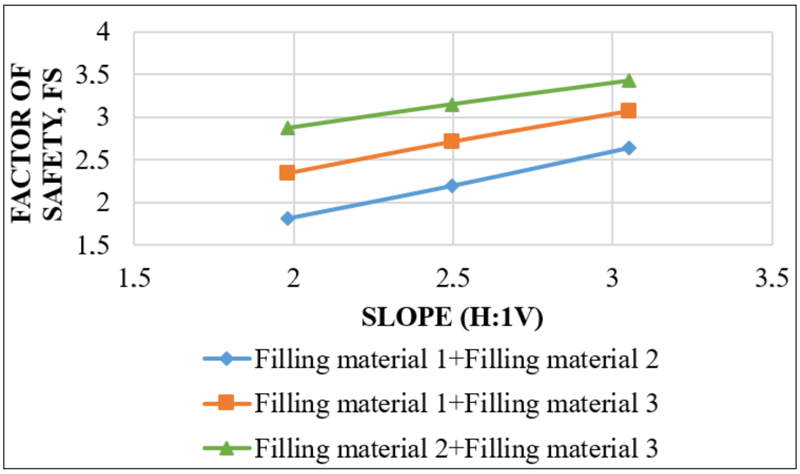

Fig. 8. Slope vs. safety factor for embankment considering two soil layers and 7 m height

4.4 Embankment Analysis Using Two Layers and 12 M Height

Table 6. 12 m embankment with different soil layers and slopes

Slope	Filling material1+ Filling material 2	Filling material 1+ Filling material 3	Filling material 2+ Filling material 3
1.5H:1V	1.59	2.23	2.30
2H:1V	2.18	2.72	2.82
2.5H:1V	2.65	3.27	3.21

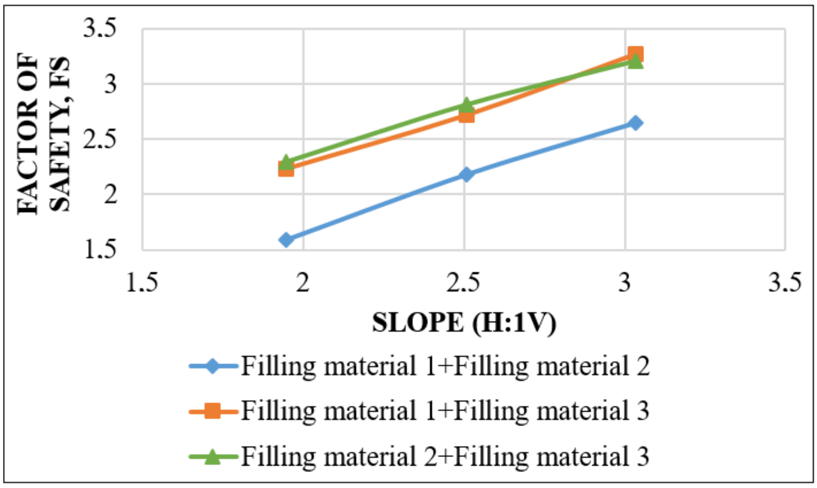

Fig. 9. Slope vs safety factor for embankment considering two filling materials (H= 12 m)

4.5 Embankment Analysis Considering Two Layers Once Height=17 m

Table 7. Embankment analyse considering varied soil layers and slopes (H=17 m)

Slope	Filling material 1+ Filling material 2	Filling material 1+ Filling material 3	Filling material 2+ Filling material 3
1.5H:1V	1.52	2.25	2.11
2H:1V	2.17	2.83	2.57
2.5H:1V	2.78	3.46	3.01

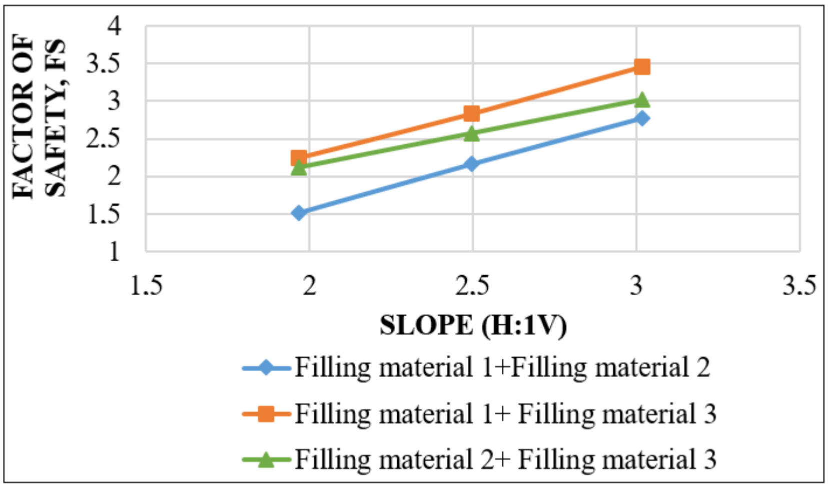

Fig. 10. Slope vs safety factor for embankment considering two soil layers once H= 17 m

4.6 Parametric Studies

Parametric studies were carried out for a range of the vetiver grass and soil parameters. The apparent cohesion of root (c_R) was considered on the following range:

$0 \leq c_R \leq 20$ kPa

Vetiver values of depth of root zone (hR) were used, namely: h_R corresponds to 1 m, 2 m , 3 m. For the properties of soils, only the effective cohesion (c′) was considered as shown in Table c′ corresponds to filling material 1=5 kPa, filling material 2= 35 kPa, filling material 3=18 kPa)

The results obtained from parametric studies are shown in Figs. 5 to 7.

Fig. 11 illustrates the safety factor values variation with the apparent cohesion o rootst (c_R) where c′ = 5 and vegetation is confined only to the slope surface. Two groups of results are offered in this figure. The broken lines are attributed to the vegetation which is confined only to the slope surface, without covering the slope toe. The solid lines correspond to the slope toe element supposed to be affected by vegetation. In general, the values increase in safety factor is related to the increase in the apparent cohesion of root (c_R). Then, where the slope toe is without vegetation, the safety factor increases to some extent initially, but drops to a lesser value after reaching a maximum value of safety factor. The safety factor is kept constant regardless of any increase in the apparent cohesion of root. For a slope with soil less cohesive (c' = 5), the failure mechanism is a superficial planar failure. This failure mechanism is prevented by the existence of vetiver roots. When the apparent cohesion of root increases, the critical failure surface moves profounder under the ground surface. When the critical sliding surface is beyond the level of the root zone, any increases in apparent cohesion of root do not contribute to an increase in the slope safety factor. As the slope toe is out of vetiver protection, this area is considered as the weak zone, and such as an increase of apparent cohesion of root in the root zone leads to failure beginning from this region. This finally activates failure because of a different mechanism of toe failure. Once the slope toe is covered by vetiver roots, the factor of safety increases with the increase in the apparent cohesion of root. Then, the slope toe seems to be the greatest critical region where vetiver vegetation is required for slope stabilisation. Therefore, in order to ensure enhanced slope stability by using vegetation vetiver, the root zone requests to spread beyond the toe region.

Fig. 11 illustrates the safety factor variation with the root cohesion (c_R) where c′ = 5 and vegetation spreads completely on the ground surface, involving the upper slope, slope surface and slope toe. The factor of safety increases as the apparent cohesion of root (c_R) increases. It is indicated that, once the whole slope is covered by vetiver vegetation, the effects on the factor of safety are weighty. Such as, when h_R = 1 m the factor of safety is increased by 31% for c_R = 20 kPa. The increase is even further important with a profounder root zone (higher h_R), as observed in Fig. 6.

Fig. 12 illustrates the factor of safety variation with the dimensionless parameter c_R/c′ when the soil effective cohesion (c′) corresponds to 5 kPa, 18 kPa, 35 kPa. The evaluation was carried when vetiver vegetation spreads all over the ground surface and h_R = 1m. The study was ended at c_R = 20 kPa for each value of soil effective cohesion (c′). It is valuable to indicate that the increase in the safety factor is further important for a slope with a small effective cohesion (c′ = 5 kPa) compared with a slope with a great effective cohesion (c′ = 35 kPa). Check of the deformed meshes revealed that, for slopes soil with upper values of effective cohesion (c′), failure produced along a deep-seated rotational sliding surface. This indicates that vetiver vegetation has a less effect on deep-seated failures once the depth of root zone (h_R) is superficial.

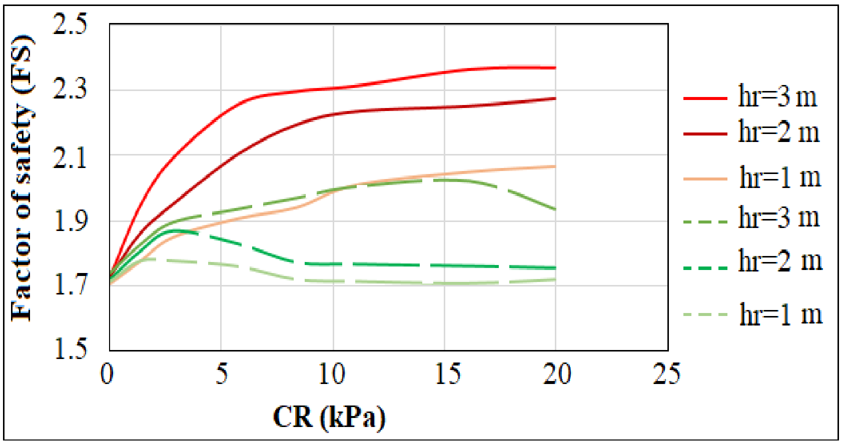

Fig. 11. Factor of safety variation with confined vegetation in the slope surface only (c ′ = 5)

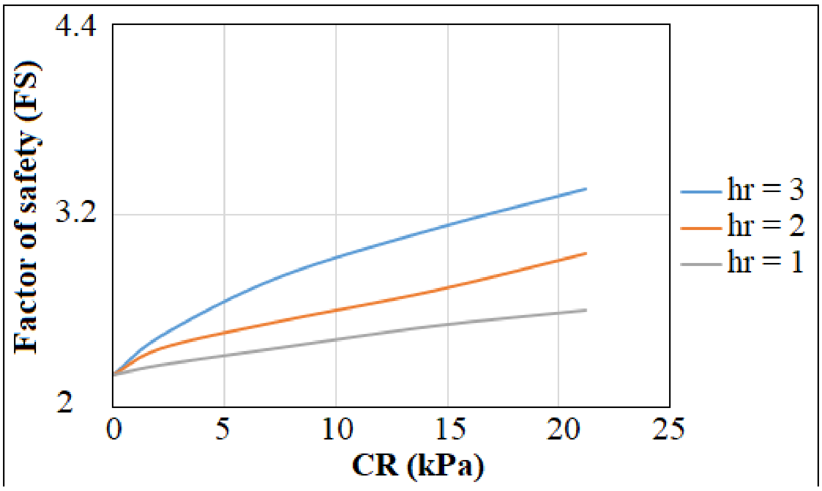

Fig. 12. Factor of safety variation when vetiver vegetation Spreading on the Whole ground surface (c ′ =5)

5. CONCLUSION

Generally, once the embankment height increases the safety factor reduces, nevertheless in the similar embankment height, slope increments then the safety factor enlarges.

The analysis of homogeneous embankment for slope stability analysis in short term the lowest safety factor regardless the slope and height is 1.51. The lowest value for 17 m height, 1.5 H: 1V slope and filling material 1.

Embankment analysis for two soil layers situation, nearly the lowest safety factor remains the same compared with the obtained before however the only difference remains once using filling material 1+filling material 2 in embankment construction.

Vegetation shows a significant role in slopes stability. Root reinforcement was reflected as an increase in apparent cohesion of soil. The apparent cohesion of root (c_R) was combined with the slope stability analysis by using the finite element method. The vetiver extent effects were considered by the root zone depth (h_R). The slope stability is sensitive to both the apparent cohesion of root (c_R) and root zone depth (h_R). The slopes stability is enhanced with an increase in the values of apparent cohesion of root (c_R) and root zone depth (h_R). Moreover, results indicated that the perfection in safety factor for a slope with vetiver vegetation cover one the whole ground surface is greater compared with vetiver vegetation cover over the slope surface only. The study has also revealed that vegetation effects are further important in slopes with small values of effective cohesion where superficial planar failures are probable to occur. Consistently, vetiver vegetation has less effect over deep-seated failure.

By joining the effects of root reinforcement in slope stability analysis, significant influence on the slopes stability has been perceived. For a more accurate modelling of natural slope, the soil suction influence and soil variability must be considered.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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