

Infiltration and stability of soil slope with vetiver grass subjected to rainfall from numerical modeling

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ABSTRACT: This paper presents the results of study on influence of vetiver grass (*Chrysopogon zizanioides*) on infiltration behaviour and stability of slopes based on unsaturated soil mechanics theory, and numerical model using parameters from past studies. The root-reinforced soil is expected to be of higher strength as well as higher permeability, which would help to reduce runoff by providing more infiltration, thus improving the soil and water conservation. Nevertheless, this would also lead to increase in pore water pressure and possibly decrease in slope stability in some cases. In this research, finite element method was used to analyze infiltration of rain into slope and limit-equilibrium method for slope stability calculation of 2 hypothetical slopes. It was found that for natural soil slope with gradient of 26° , the 2-metre deep vetiver grass roots appeared to increase the pore water pressure only marginally and thus the stability of the soil was improved by reinforcement of the roots. However, for a weathered rock slope of about 60° , the 0.8 m deep vetiver roots could potentially provide a pathway for water infiltration, and increase the pore water pressure and thus reduced the factor of safety of the slope by about 10%.

1 INTRODUCTION

Slope failure and erosion problems have increasingly become more frequent around the world, causing damage to infrastructure and sometimes leading to loss of people's lives. Soil-Bio engineering or the use of vegetation to prevent shallow slides and erosion has been historically applied in many parts of the world. Recently, this green approach has received more attention among practitioners and researchers worldwide due to its relatively low cost, aesthetic and environmental value, as well as sustainability (e.g. Gray & Sotir, 1996, Rahardjo et al., 2012).

In many tropical and sub-tropical countries, vetiver grass (*Chrysopogon zizanioides* or formerly, *Vetiveria zizanioides*) have been used extensively for shallow slide stabilization and erosion control (e.g. Hengchaovanich, 1998, Truong et al., 2008). Normally, planted as hedgerows parallel to the slope contour, vetiver grass has a very dense fine vertical root system that penetrates as deep as 3-4 meter in some applications, making it very effective for slope stabilization, reduction of runoff erosive energy and sediment trap. Its application ranges from soil-water conservation, slope stabilization as well as pollution-control at landfills. Its popularity is due to the ease of use, tolerance, low-cost and effectiveness where applied correctly. For example, in Thailand, the vet-

iver grass was successfully implemented for erosion control and slope stabilization along the Yadana gas pipeline right-of-way zone running from Myanmar to Thailand (Tansamrit, 2003).

However, there are many aspects of influence of vegetation on slope stability as shown in Figure 1, some of which are beneficial and some can be destabilizing. For example, canopy interception of rainfall and evapotranspiration will reduce pore water pressure leading to increase in shear strength. Root fibers reinforce the soil mass, thus increasing its shear strength too. However, vegetation-covered and root-permeated ground surface are normally of higher permeability and infiltration rate (see e.g. Styczen & Morgan, 1995) This increased infiltration would lead to lower run-off and consequently less erosive energy which is understandably beneficial for erosion control (e.g. Curtis & Claassen, 2007). Yet, it may also bring about increase in pore water pressure which would subsequently destabilize the slope. In particular, vetiver grass, which is considered one of the deepest roots amongst all plants, in theory, may provide a pathway for water infiltration to a greater depth. There are thus concerns of this theoretical risk of increased infiltration and destabilizing effect due to vetiver grass on steep slope. In 2011, H.M. the king Bhumibol of Thailand, the great patron of vetiver applications, even suggested practitioners to exercise certain caution when applying vetiver on steep

slopes. It is thus the objective of this study to explore both advantage and potential risk of vetiver grass on slopes by way of numerical modeling. The finite element method was used to analyze infiltration of rain into slope and limit-equilibrium method for slope stability calculation of 2 hypothetical slopes with gradient of about 27° and 60°. For both cases, the slopes were modelled with and without vetiver row in order to compare the effects of vetiver on stability.

;where, c' = effective cohesion intercept, c^r = root cohesion, σ_n = normal stress, ϕ' = effective angle of shearing resistance, u_w = pore water pressure (positive or negative), ϕ'' = angle of shearing resistance due to pore water pressure or suction (for unsaturated case, $u_w < 0$, and $\phi'' = \phi^b$, but for saturated case, $u_w > 0$, then $\phi'' = \phi'$). Note that Equation (2) assumes that pore air pressure $u_a = 0$.

The value of root cohesion can be estimated using Equation (3) (Wu et al., 1979)

$$c^r = t_R \left[\frac{A_R}{A} \right] (\sin \theta + \cos \theta \tan \phi') \quad (3)$$

;where t_R = mobilized root tensile stress, $\frac{A_R}{A}$ = Ratio between root and total area; θ = Shear distortion angle in the shear zone.

3 CASE STUDY 1: NATURAL SLOPE (2:1, H:V)

3.1 Slope profile

For case study 1, the modeled slope, as shown in Figure 2, consists of top soil (0.2m in thickness), which is underlain by soils 1 & 2 and bedrock. The total depth from ground surface to bedrock is 2 metre. The slope gradient is about 26.6 degree, which is similar to the condition of failed natural slope in Uttaradit province, Northern Thailand (Jotisankasa & Tapparnich, 2010).

As explained earlier, the slope was modelled with and without vetiver row in order to compare the effects of vetiver on stability. As shown in Figure 1, in the with-vetiver case, the vetiver root zone had the depth of 2 meter (i.e. rooted down to bedrock) and width of 0.2 m. The spacing between vetiver row was 1 meter (in horizontal direction) and the total length of slope was 29 meter.

As for the without-vetiver case, as shown in Figure 3, the slope profile was the same as for the with-vetiver case, except that there was no vetiver root zone in the modeled slope.

3.2 Soil properties

Material properties used in this analysis were based on past studies as shown in Table 1 and Figures 4&5. The soil properties were those of residual soils derived from weathered argillaceous rock (Shale and Mudstone) from Uttaradit province where widespread shallow landslides took place in 2006 (Jotisankasa & Tapparnich, 2010, Tapparnich, 2010).

In the stability analysis, bedrock was modeled as impenetrable boundary, while in the seepage analysis, the permeability function of the bedrock was the assumed parameter for slightly jointed sedimentary rock (Blyth & de Freitas, 1984) and the SWCC was assumed to have air-entry suction greater than 100 kPa.

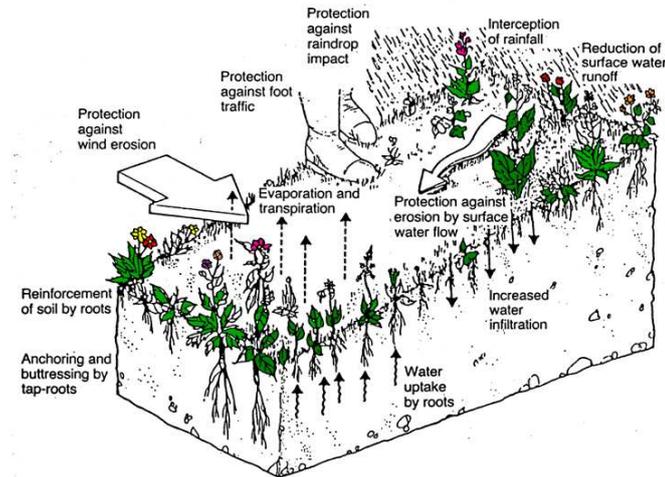


Figure 1. Various effects of vegetation on slopes (Coppin & Richard, 1990)

2 THEORY

2.1 Variably saturated seepage

Infiltration behavior of slope can be studied using Richard's and continuity equation as shown in (1).

$$\frac{\partial}{\partial x} \left[k_x \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[k_y \frac{\partial h}{\partial y} \right] + Q = m_w \left[\frac{\partial u_w}{\partial t} \right] \quad (1)$$

where, k_x and k_y is the permeability in x and y direction respectively, h = total hydraulic head, Q = applied boundary flux, u_w = pore water pressure, and m_w = gradient of the soil-water characteristic curve.

It should be noted that for variably saturated soils, permeability, water content as well as shear strength are now functions of pore water pressure which can be positive or negative (i.e. suction). The purpose for solving equation (1) is to determine the distribution of pore water pressure in response to rainfall infiltration, which would then be used in stability calculation.

2.2 Soil-root composite shear strength

Shear strength (τ) equation for variably saturated soil with root reinforcements can be expressed as (2);

$$\tau = c^r + c' + \sigma_n \tan \phi' - u_w \tan \phi'' \quad (2)$$

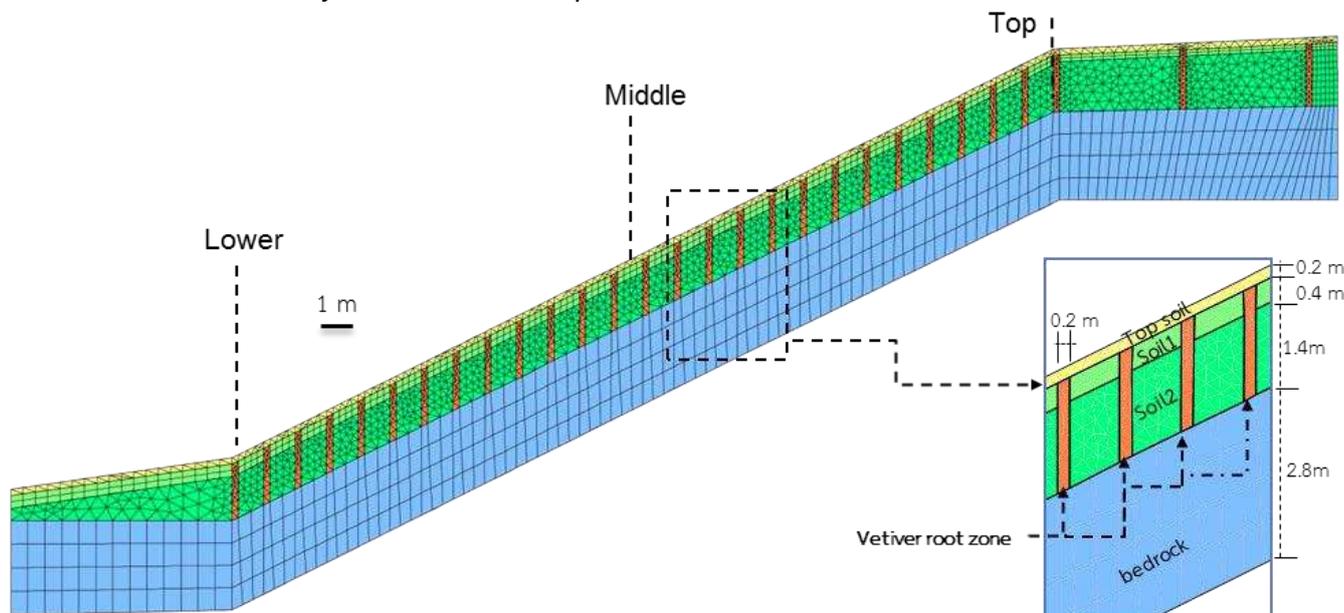


Figure 2. Slope geometry and finite element mesh for case study 1 (with vetiver rows)

Table 1. Material properties assumed in case 1 analysis (26.6° slope)

Material	γ_{sat} kN/m ³	$c'+c^f$ kPa	ϕ' deg.	ϕ^b deg	γ_{moist} kN/m ³	
Top soil	17	22.8	17.6	13.9	16.5	*
Soil 1	18.5	2	32	27.7	18	*
Soil 2	18.7	2	32	27.7	18	*
Vetiver root zone	18.5	11	32	27.7	18	**

Source * Jotisankasa & Tapparnich (2010), Tapparnich (2010), ** Hengchaovanich (1998)

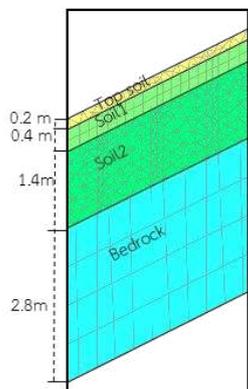


Figure 3. Ground profile for case study 1 (without vetiver)

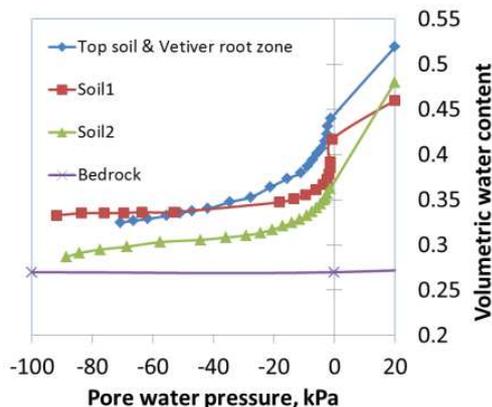


Figure 4. Soil-water characteristic curves used in the analysis

3.3 Seepage and pore water pressure analysis

Seepage analysis was conducted in this study using the SEEP/W finite element software. For the initial condition, the steady state analysis was performed with the flux boundary condition at the upper surface specified as 1.077×10^{-7} m/s (300 mm/month), which was the average monthly rainfall during rainy season in Thailand. The left-side boundary in Figure 2 was specified as zero pressure head, while the base and right-side boundaries were specified as impermeable. During transient analysis, the upper boundary condition was specified as 1×10^{-6} m/s (86.4 mm/day) and the period of rainfall continued for 48 hours.

Figure 6 shows the pore water pressure distribution along three locations in slope with vetiver row at different times. It can be seen that at initial stage, the pore water pressure was higher at location closer to the toe and became more negative at the top. As rainwater infiltrated the ground, the pore water pressure increased more dramatically at the middle and upper part of the slope, while at the toe, the pore water pressure remained practically unchanged.

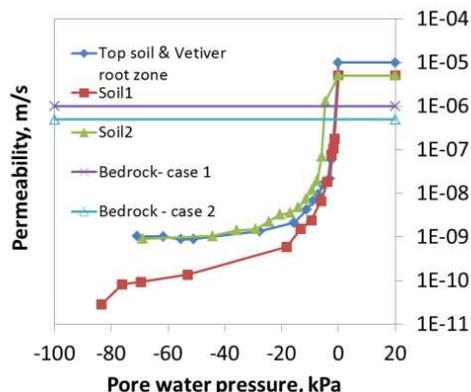


Figure 5. Permeability functions used in the analysis

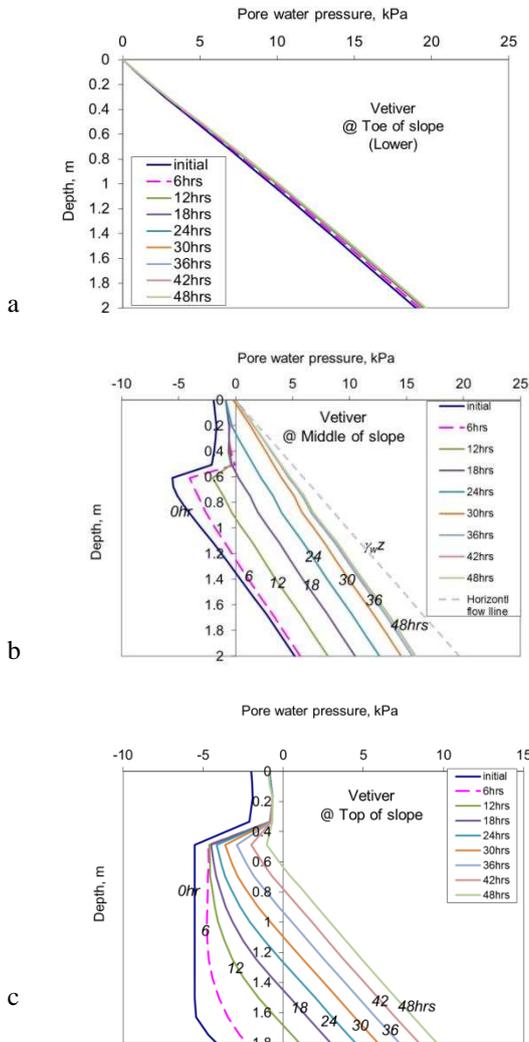


Figure 6. Pore water pressure distribution from case 1 analysis (with vetiver)

From Figure 6b, it can be seen that after 30 hours (total rain about 100 mm), the pore water pressure became positive with approximately linear variation expressed by the equation: $u_w = 0.74 * \gamma_w Z$, where Z is the depth from ground surface. This corresponded to nearly horizontal seepage out of slope surface. So it can be seen that, after accumulated rainfall reached about 100 mm, all the suction in the slope was destroyed and positive pore pressure critically developed. This amount of critical rainfall agreed well with past records of slope failure (Jotisankasa et al., 2008)

In Figure 7, pore water pressure distributions for slopes with and without vetiver rows are compared at the location top of slope. It can be seen that there was only slight difference between the two cases. Yet, for slope with vetiver rows, the root zone appeared to conduct water to a greater depth, resulting in slightly lower pore water pressure from zero to 0.5 m depth, while having marginally greater pore pressure at greater depth. By and large, there is not much significant difference between the pore water pressure of 26° slopes with or without vetiver.

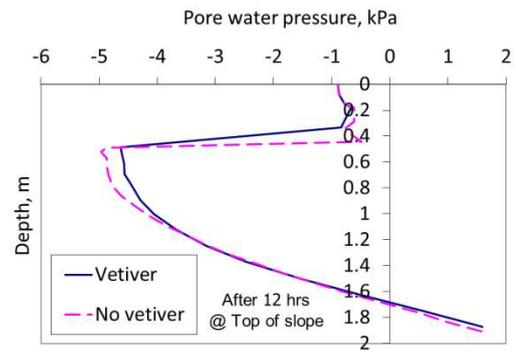


Figure 7. Pore water pressure after 12 hours of rain (43 mm of rain) for case 1 (with and without vetiver)

3.4 Slope stability analysis

The values of pore water pressure variation with time were then used in stability calculation to determine the change of factor of safety with accumulated rainfall as shown in Figure 8. The General Limit Equilibrium (GLE) method in software SLOPE/W was employed and the critical failure surface is shown in Figure 9. The slope without vetiver grass appeared to fail (FS=1) when the total rainfall reached about 120-170 mm and the slope with vetiver rows was always of higher factor of safety throughout. It can be said that the increased cohesion due to roots more than offsets the higher permeability of root zone that may induce deeper infiltration into slopes, at least for the case of 26.6° slope.

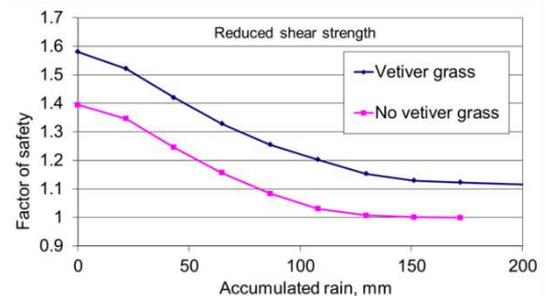


Figure 8. Factor of safety and accumulated rain for 26.6° slope with and without vetiver rows.

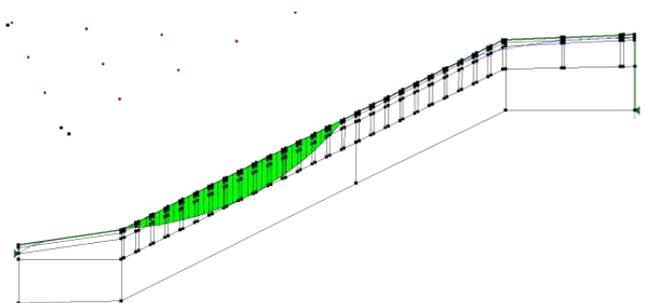


Figure 9. Failure surface for the case without vetiver (accumulated rain of 172 mm)

4 CASE STUDY 2: CUT SLOPE (1:2, H:V)

4.1 Slope profile and material properties

For case study no 2, the modeled slope had a gradient of about 60 degree and the FEA mesh are as shown in Figure 10. This slope was typical of cut slopes in weathered rock in Thailand. The vetiver row was present in each 2-meter high bench and the root zone was 0.2 m wide and only 0.8 m deep. The soil-water characteristic curve and permeability function of the modeled materials are shown in Figures 4 and 5. The shear strengths are shown in Figure 11 which are typical of weathered weak claystone. Again, both cases of slope with and without vetiver rows were studied in order to investigate the influence of the grass on stability.

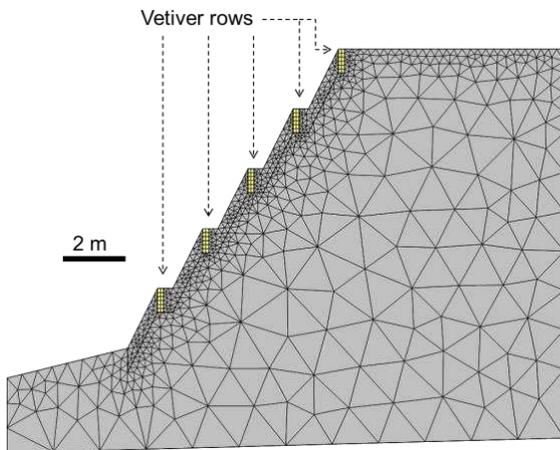


Figure 10. Slope geometry and finite element mesh for case study 2 (with vetiver rows)

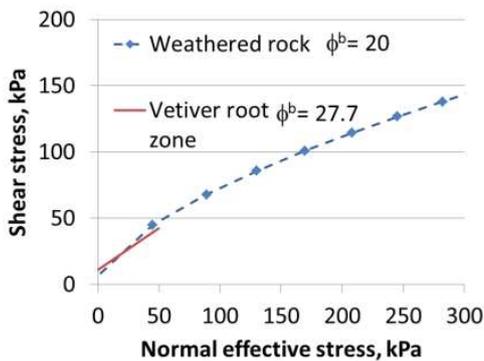


Figure 11. Shear strength of materials for case 2

4.2 Seepage and stability analysis

The procedure followed in the seepage analysis of case No 2 was the same as in the case No 1. The initial condition of pore water pressure, corresponding to an upper boundary flux of 300 mm/month, is shown in Figure 12. Figure 13 shows the pore water pressure from transient seepage analysis at 24 hours (accumulated rain of 86.4 mm) for both vetiver and no vetiver cases. It can be seen that, with vetiver hedgerows on slope, groundwater can infiltrate to a greater depth through the root zone, resulting in

higher pore water pressure in the slope. Without the vetiver rows, part of the rainfall would not permeate the ground and tend to become runoff.

Based on this pore water pressure distribution, slope stability analyses were performed for both cases (with & without vetiver) at different accumulated rainfalls and the results are shown in Figure 14. It can be seen that the factor of safety for the slope with vetiver is about 10% lower than the slope without vetiver. This is due to the increased pore water pressure induced from increased infiltration through the root zone. Figure 15 shows the failure surface (FS=0.969) of the slope with vetiver rows, after 48 hours of rain (172 mm). Notably, the failure surface extended deeper than the root zone of the vetiver and hence it can be said that the influence of the root reinforcement in this case does not contribute to the stability.

Various assumptions made in this study still need to be explored further to confirm the validity of this finding. In particular, the actual depth of the vetiver roots in the field that can penetrate the bedrock still needs to be confirmed. In addition, this study only investigated mass stability and neglected the erosion due to runoff which is also another important aspect of slope failures in Thailand.

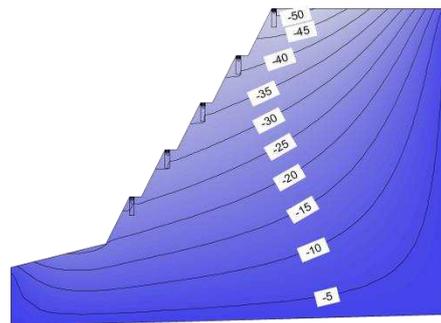


Figure 12. Contours of initial pore water pressure (kPa) for steady state condition (upper boundary flux = 300 mm/month)

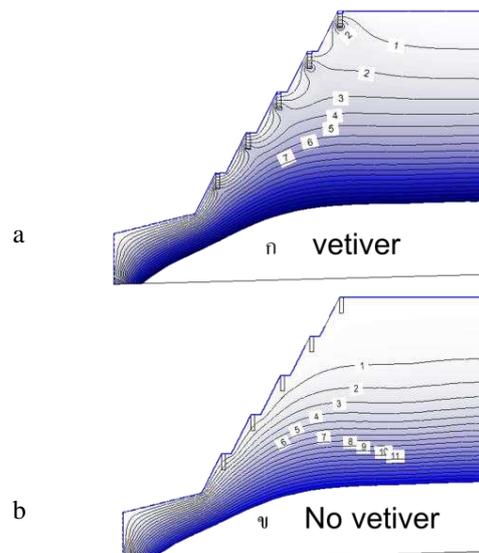


Figure 13. Contours of pore water pressure (kPa) after 24 hours of rain (86.4 mm of rain) a) with vetiver; b) without vetiver

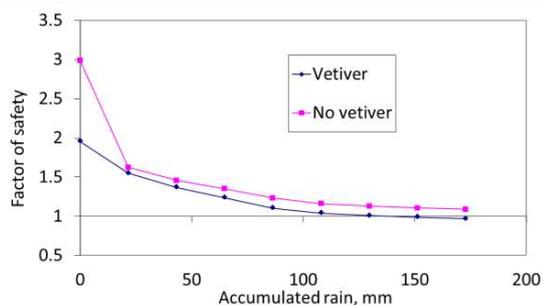


Figure 14. Factor of safety and accumulated rain for 60° cut slope with and without vetiver rows.

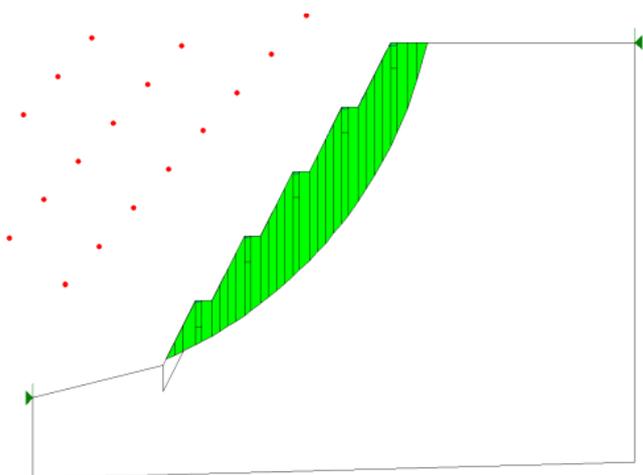


Figure 15. Failure surface for 60° cut slope with vetiver (at accumulated rain of 172 mm)

5 CONCLUSIONS

Even though the presence of vegetation roots can help reinforce the soil mass, thus increasing its shear strength, root-penetrated soil may also have higher permeability which leads to increased infiltration into slope. There was concern that vetiver grass which is particularly of very deep roots might pose adverse effects on slope stability in some circumstances. The SEEP/W finite element software was thus used to analyze infiltration of rain into slope and the SLOPE/W limit-equilibrium software for slope stability calculation of 2 hypothetical slopes, with and without vetiver grass. It was found that for natural soil slope with gradient 26°, the 2-metre deep vetiver grass roots appeared to increase the pore water pressure only slightly and the stability of the soil was mainly improved by reinforcement of the roots. However, for a weathered rock slope of about 60°, the 0.8 m deep vetiver roots could potentially provide a pathway for water infiltration, increased the pore water pressure and thus reduced the factor of safety of the slope by about 10%.

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