Stabilization of Cut Slopes in Highways by Surface Drainage and Vegetation

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ABSTRACT: At number of locations in Sri Lanka, deep cuts were made in natural slopes for the construction of expressways. These slopes are made of residual soil and the parent rock is metamorphic. In most cases the ground water table is low and significant matric suctions prevail in the soil during dry periods of weather. With the infiltration of rainwater, the matric suction will be lost and even perched water table conditions could be developed. The presence of surface protecting vegetation and drainage measures such as berm drains will reduce the infiltration. Deep roots present will provide a nailing effect. This behavior was studied by modeling the process by Geoslope SEEP/W programme. Stability of the slope was assessed by the SLOPE/W after incorporating the changes in the pore pressure regime. The results of the study illustrated the effectiveness of surface protecting vegetation and deep roots in maintain reasonable safety margins in the slope during periods of heavy rain.

1 INTRODUCTION

Deep cuts were done at number of locations in residual soil formations for the construction of expressways. The parent rock is metamorphic and due to inherited variable nature in the mineralogical structure in the parent rock and weathering under tropical conditions with high rainfall, abrupt changes are seen in the soil profile forming the slopes. There are zones of contrasting permeability and shear strength parameters. The ground water table is usually low during periods of dry weather and soil forming the slope possesses significant matric suction.

Rainfall has been the major triggering factor in majority of slope failures in tropical countries such as Sri Lanka experiencing high seasonal rainfalls. Rainfall leads to loss of matric suction, development of perched water table, rise of the groundwater level and soil erosion. This in turn results in a decrease in shear strength of residual soil affecting the stability adversely.

Sealed berm drains and cascade drains together with the protective vegetation cover on slopes can effectively control the slope hydrology and stability. The vegetation cover on slopes could deflect the rainwater and significantly retards the rate of infiltration and rise in the groundwater table. Thus the reduction of shear strength during a prolong rainfall can be minimized. Deeper and stronger roots can have a reinforcing effect such as with soil nailing.

2 METHODOLOGY ADOPTED

The finite element based computer package in the Geo-Slope family SEEP/W (2007) was used to model the infiltration through the unsaturated soil slope. The transient flow equations were solved using the finite element method incorporated in the SEEP/W program. The results of the infiltration modeling were imported to slope stability analysis program SLOPE/W to carry out the stability analysis. Kulathilaka and Sujeevan (2011) presented the changes of pore pressure regime and stability in a slope when no drainage measures were adopted. Kulathilaka and Kumara (2011) presented the behavior of a slope where berm drains and slope surface protecting vegetation were used. Sealed berms and slope surface protected by vegetation were modeled by using thin soil layers of lower value of coefficient of permeability. In this research, the presences of deep roots were simulated in the stability analysis by inserting reinforcing elements of appropriate length and directions in the form of soil nails. Effects of continuous as well as intermittent rainfall were analysed.

The most fundamentally important data for the analysis are the Soil Water Characteristic Curve (SWCC) and the permeability function. Two standard curves appropriate for the types of soil encountered in the study area (Sun et al, 1998) in the absence of exact experimental data.

3 INFILTRATION ANALYSIS

A typical cut slope of height 53m from Southern Expressway was used in the analysis. Although the soil profiles are very non uniform the slope is considered to be made of a uniform residual soil. The gradient of the cut slope is 1:1.267 with 2m wide berms at every 7.5m height difference. (Fig. 1). Sealed berm layer was represented by a 100 mm thick soil layer having saturated conductivity and volumetric water content $1x10^{-20}$m/s and 0.01 respectively. Vegetation layer was represented by a 100 mm thick soil layer with same saturated volumetric water content as residual soil. Saturated hydraulic conductivity values of 10^{-6}m/s and 10^{-7}m/s were used to simulate different types of vegetation.

Rainfall was applied to the soil surface and the seepage face boundary condition was applied to the soil surface to run off over the surface of the slope if the rainfall is greater than the saturated hydraulic conductivity of the soil. Boundary flux, q, which is equal to the rainfall intensity, was applied to the surface of the slope. Nodal flux, Q, was taken to be zero at the sides of the slope above the water table. The bottom of the slope simulates a no flow zone. Positive pore water pressures at the initial condition for all the analyses were assumed to be hydrostatic and matric suction was given an upper limit of 100 kN/m^2(Fig. 2). The geological conditions are quite complex but this paper present only the analysis for the case of a uniform slope.

Analyses were carried out for rainfall intensities of 5mm/hr and 20mm/hr. Continuous rainfall and 12 hr and 24 hr intermittent rainfall were considered. The residual soil was assigned a saturated hydraulic conductivity value of $1x10^{-5}$m/s and a saturated volumetric water content of 0.45.

The changes in the pore pressure regime of the slope were presented by plotting the pore water pressure distribution along two vertical sections (Section A and Section B) in the cut slope. The variation of pore pressure regime for 5 mm/hr rainfall without any surface protecting vegetation is presented in Fig. 2. The variation when there is surface protecting vegetation is presented in Fig. 3. Similar pore pressure variation plots for a rainfall intensity of 20mm/hr are presented in Fig. 4 and Fig. 5 respectively. The loss of matric suction with continued rainfall is well illustrated in the plots. With the rainfall of greater intensity a perched water table condition has developed. The effectiveness of surface protecting vegetation in reducing the infiltration is also evident from the comparison of plots. When the rainfall is intermittent there was time for recovery of matric suction and perched water table condition was of much lower significance. The surface protection vegetation was quite effective in reducing the infiltration in high intensity rainfall. This is illustrated in Fig. 6 and Fig. 7.

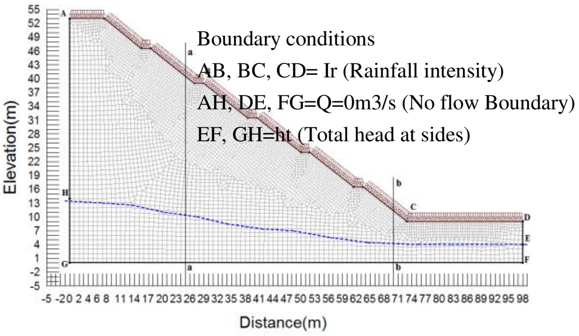

Fig. 1 Slope cross section used in the analysis

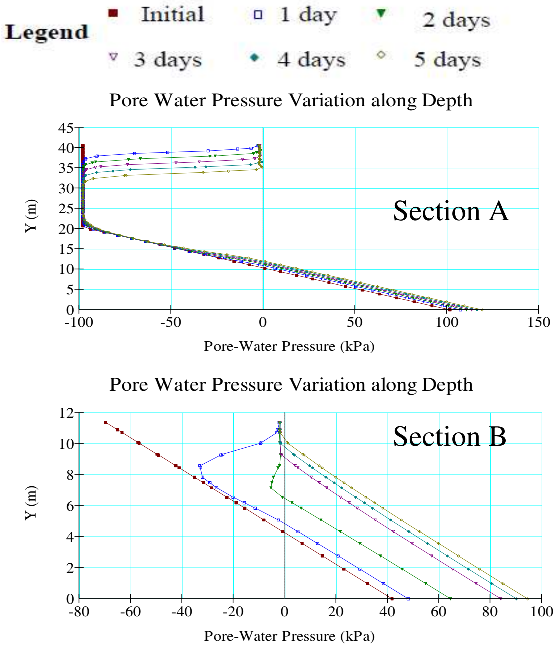

Fig. 2 Pore water pressure variation for 5mm/hr continuous rainfall - without surface protecting vegetation

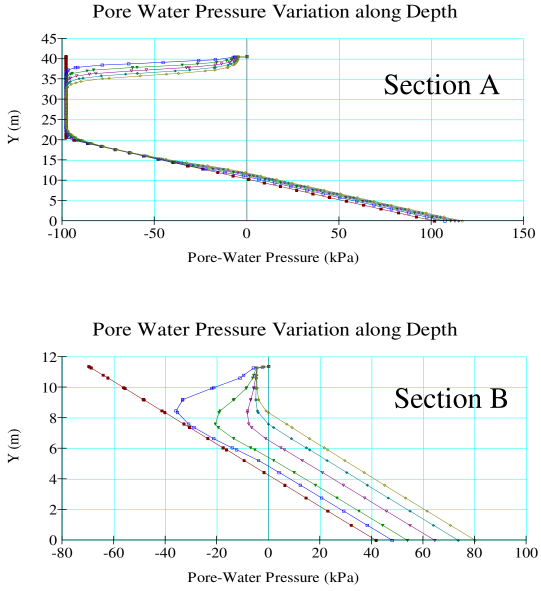

Fig. 3 Pore water pressure variation for 5mm/hr continuous rainfall) - With surface protecting vegetation.

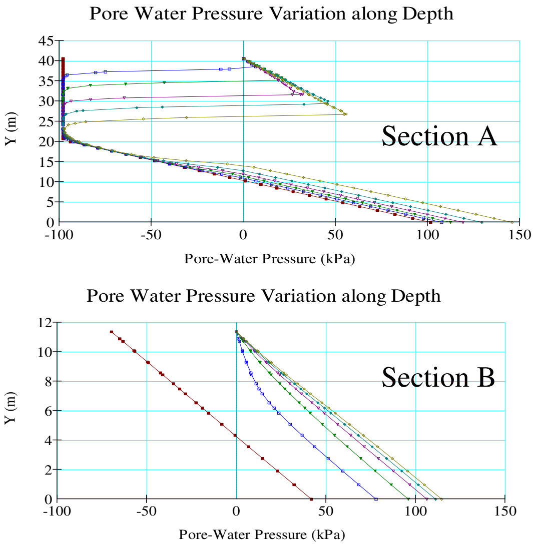

Fig. 4 Pore water pressure variation 20mm/hr continuous rainfall - Without surface protecting vegetation

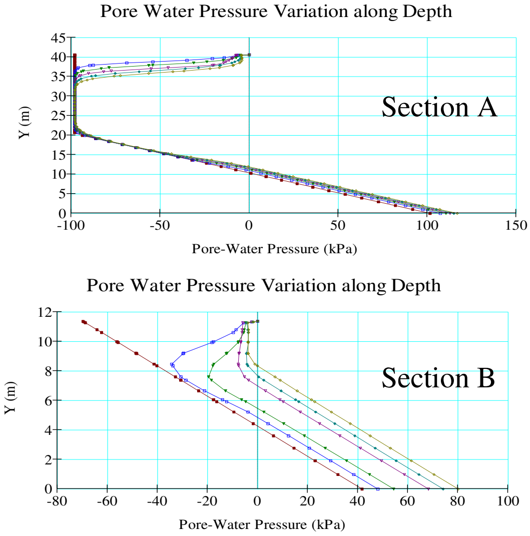

Fig. 5 Pore water pressure variation 20mm/hr continuous rainfall - With surface protecting vegetation

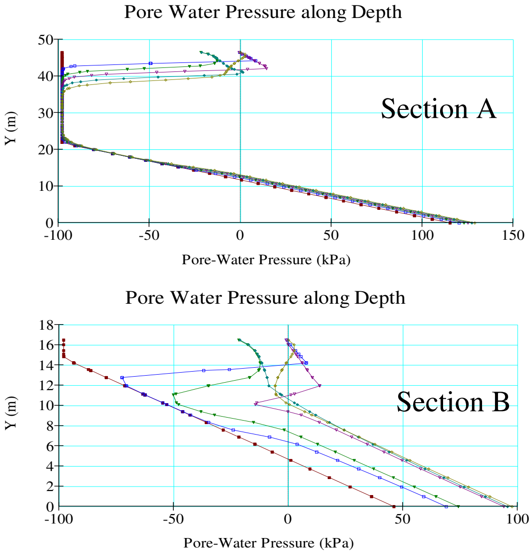

Fig. 6 Pore water pressure variation 20mm/hr 24 hr intermittent rainfall-Without surface protecting vegetation

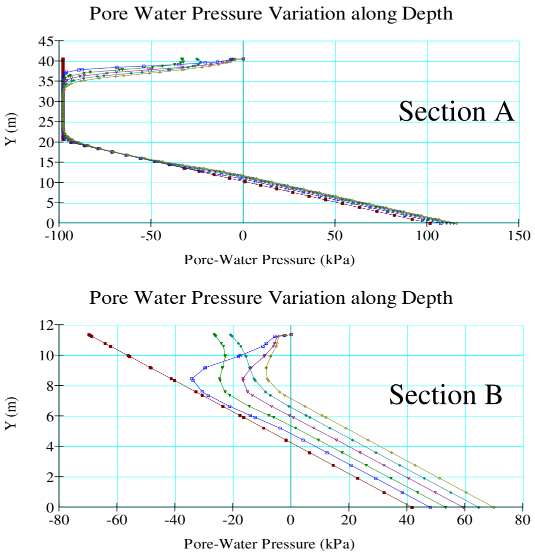

Fig. 7 Pore water pressure variation 20mm/hr 24 hr intermittent rainfall - With surface protecting vegetation

4 STABILITY ANALYSIS

The variation of the safety margins in the slope under different conditions of seepage analysed above was assessed by conducting stability analyses through the SLOPE/W (2007) software. The pore water pressure changes computed through SEEP/W software were incorporated in the stability analyses. Possibilities of both circular and non circular failure surfaces were considered and the stability analyses were carried out with the Spencer's method. Effective Shear strength parameters $c=5kN/m^2$, $\phi' =30$ and $\phi_b= 24$ were used.

Analyses were done for the cases of; soil slope without surface protection, soil slope with surface protection and soil slope with deep roots inducing a nailing effect as well. The root arrangement considered in this case is presented in Fig. 8. In the plane strain analysis this root system was assumed to exist at 3m intervals. The roots were modeled as nails of drill hole diameter 50 mm and tensile strength of 200 kN.

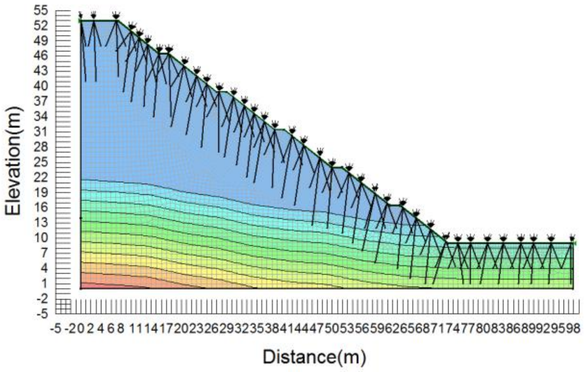

Fig. 8 Root configuration used

The reduction of the factor of safety as the rain progressed is presented in Fig. 9 and Fig. 10 for rainfalls of 5mm/hr and 20 mm/hr respectively. A typical critical failure surface at an early stage (day 2) is depicted in Fig. 11 and at day 5 is depicted in Fig. 12.

When the surface protection vegetation is present the reduction of the FOS was very effectively controlled for both rainfall intensities in a continuous rainfall. With an intermittent rainfall the FOS reduction over the five day period was very much lower. With the intermittent rainfall of intensity 20mm/hr, some notable increase of FOS was seen during the dry day. This is due to the downward movement of pore water making a deeper failure surface critical. The reinforcing effect of roots is not significant in early stages. Its influence on FOS was visible only in the day 5. In early days the critical failure surfaces are quite deep (Fig 11). A typical critical failure surface extends much deeper than the roots and roots cannot generate a reinforcing effect. At later stages the critical failure surface is shallower (with a lower FOS) and the roots of same length are more effective.

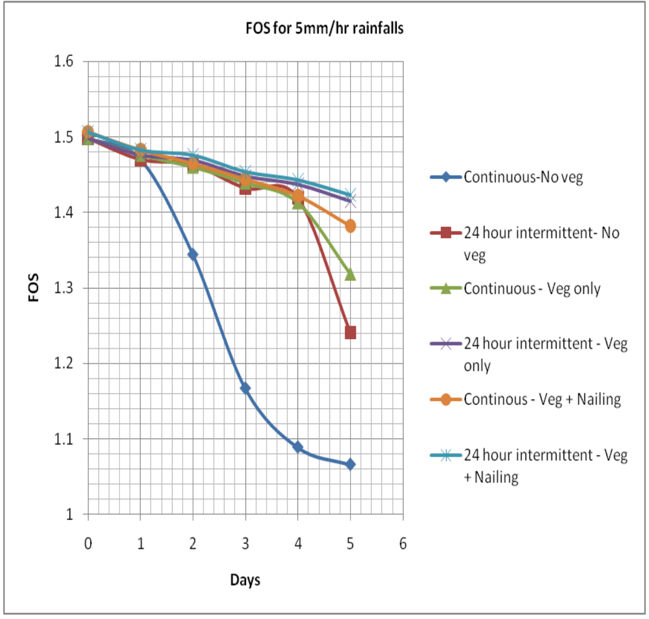

Fig. 9 FOS variation for 5mm/hr rainfall

5 CONCLUSIONS

The reduction of safety margins of a slope with continuous rainfall and effectiveness of surface protection vegetation to control the said reduction was illustrated using a typical cut slope profile in residual soil.

With intermittent rainfall, there was time to regain some lost matric suction and the reduction of FOS with time was lower.

If the roots are to apply a reinforcing effect such as with soil nailing, deeper roots should be present at closer spacing.

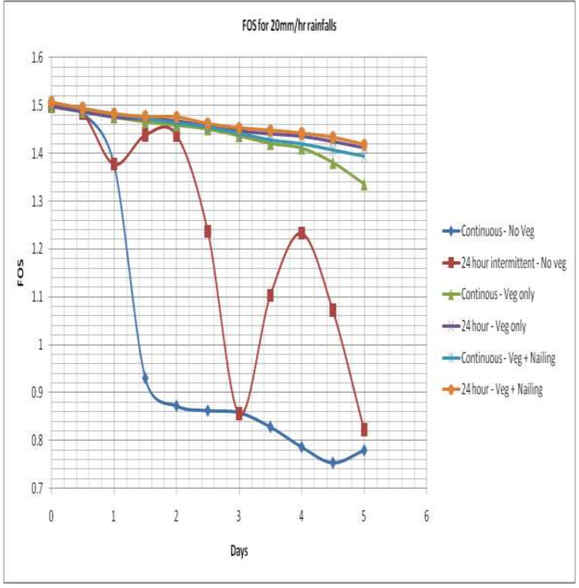

Fig. 10 FOS Variation for 20mm/hr rainfall

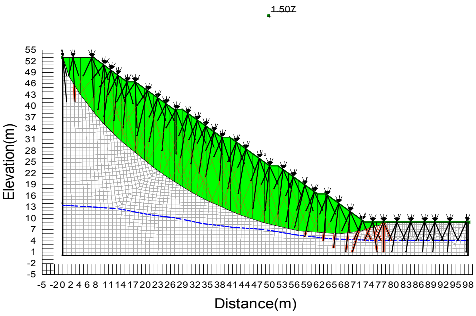

Fig. 11 Critical failure surface at day 2

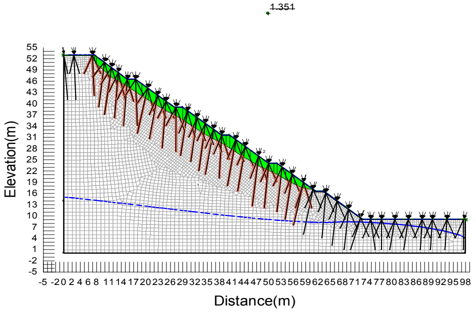

Fig. 12 Critical failure surface at day 5

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