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Article · January 2005

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Effect of Surface Cover on Water Infiltration Rate and Stability of Cut Slope in Residual Soils

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ABSTRACT

Rainfall has been considered the cause of the majority of slope failures and landslides that happened in regions experiencing high seasonal rainfalls. Basically, it is well known that infiltration impairs slope stability, but since it is often not measured off directly from the field, its assessment often relies on vague correlation with rainfalls and runoff. Conventionally, infiltration of water is not included in the slope stability analysis. However, most of the slope failure and landslides occurred after prolonged heavy rainfall or antecedent rainfall. The mechanism of the failures was mainly due to the lost of matric suction of soils by rainwater. When the rainwater infiltrates into the slopes, it will start to saturate the soil, i.e. reduce the matric suction. The rate of water infiltration into the soil and its effect on suction is expected to be influence by the types of surface cover, as well soil porosity/weathering grades, and angle of the soil slopes. This paper presents results of a field study on the effect of surface cover on the water infiltration rate into a cut slope of unsaturated residual soil. A parametric study was also done to examine the effect surface cover on the factor of safety of soil slope using the Seep/W and Slope/W programs. The soil infiltration rate as measured from the field test showed an increase from the fully vegetated slope with geosynthetic net, to cut grass slope with geosynthetic net, to geosynthetic net, and to bare surface slope only. For a particular surface cover/condition, soil of weathering grade III had higher infiltration rate compared soils of intermediate grade (IV – III), grade IV and grade V. The factor of safety obtained from analysis by incorporating matric suction, was much higher than the factor of safety obtained from the conventional slope stability analysis without matric suction.

There was a trend of reduction in factor of safety with rain, in particular for slopes with the lesser cover.

KEYWORDS: Cut Slope, Landslide, Partially Saturated Soil, Residual Soil, Vegetation

INTRODUCTION

Rainfall has been considered the cause of the majority of slope failures and landslides that happened in regions experiencing high seasonal rainfalls (Brand 1984, Shaw-Shong 2004). Basically, it is well known that infiltration impairs slope stability, but since it is often not measured off directly from the field, its assessment often relies on vague correlation with rainfalls and runoff. Correlation between rainfall and infiltration, thus slope stability involves large number of factors. Some of these factors, such as rainfall duration and intensity, slope surface cover, degree of saturation, slope angle, permeability ratios and perched water table are extremely difficult to evaluate.

Conventionally, infiltration of water is not normally included in slope stability analysis. Many of the steep slopes were designed based on experiences. Most of the slopes failure or landslides occurred after prolonged heavy rainfall or antecedent rainfall. The mechanism of the failures was mainly due to the lost of matric suction of soils by rainwater. When the rainwater infiltrates into the slopes, it is known that it will start to saturate the soil, i.e., reduce the matric suction. The wetting front of rainwater will continue to move into the soil even after the rain stopped. Movement of the wetting front stops when an equilibrium or steady state condition is achieved.

Matric suction is one of the main stress variables in unsaturated soil theory (Fredlund and Morgenstern 1977, Fredlund and Rahardjo 1987). The existence of matric suction will increase the strength of the soil. A deep ground water table condition is normal in hilly area of the tropical countries. In this case, the negative pore water pressure or matric suction plays an important role in controlling the soil shear strength and consequently the stability of many steep slopes. Shallow landslides often occur in steep residual soil slopes after heavy and prolonged rainfall. When water starts to infiltrate into the soil, the matric suction especially near the ground surface will slowly reduce and become zero as the soil approaches saturated condition. The significant reduction in matric suction is known to cause a decrease in the soil shear strength that subsequently produces shallow landslides.

Studies on water infiltration have always been part of hydrology. Water infiltration forms the link between surface and subsurface hydrology. Infiltrated water must be quantified and subtracted from the surface runoff in flood prediction studies and surface water management. Numerous researchers have actually incorporated infiltration into the slope stability analysis of the residual soil, e.g. Othman (1989), Anderson (1991), Affendi and Ali (1994), Suhaimi (1997) and Ali and Rahardjo (2004). In most of the analysis of slope stability, the infiltration rate of the water into soil is assumed uniform throughout the slope. The soil is also assumed homogeneous except in some layered bedding problem.

This paper presents results of a field study on the effect of surface cover on the water infiltration rate into a cut slope of unsaturated residual soil. A parametric study was also done to examine the effect surface cover of the factor of safety of soil slope using the Seep/W and Slope/W programs.

FIELD SITE

The field site was a cut slope of approximately 40m high along a link road near the Kuala Lumpur International Airport, Sepang, Malaysia. The slope basically comprise of residual soils of weathered sandstone. The soils are generally yellowish brown in color and consist mainly of fine sands and silts.

The cut slope was mapped for the weathering grades, based on the commonly used classification of Little (1969), and Kamoo and Mogana (1988) (see Table 1).

Table 1. Classification of weathering profile over sedimentary and meta-sediment rock in Peninsular Malaysia (Komoo and Mogana 1988)

Weathering classification Term	Zone	Description
Residual soil	VI	All rock material is converted to soil. The mass structure and material fabric (texture) are completely destroyed. The material is generally silty or clayey and shows homogenous color.
Completely weathered	V	All rock material is decomposed to soil. Material partially preserved. The material is sandy and is friable if soaked in water or squeezed by hand.
Highly weathered	IV	The rock material is in the transitional stage to form soil. Material condition is either soil or rock. Material is completely discolored but the fabric is completely preserved. Mass structure partially present.
Moderately weathered	III	The rock material shows partial discoloration. The mass structure and material texture are completely preserved. Discontinuity is commonly filled by iron-rich material. Material fragment or block corner can be chipped by hand.
Slightly	II	Discoloration along discontinuity and

weathered		may be part of rock material. The mass structure and material texture are completely preserved. The material is generally weaker but fragment corners cannot be chipped by hand
Fresh rock	I	No visible sign of rock material weathering. Some discoloration on major discontinuity surfaces.

Figure 1 shows a cross section of the cut slope. Base on the geological formation, the cut slope profile falls under the following weathering grades:

Berm 1 – Weathering grade V

Berm 2 – Weathering grade IV

Berm 3 – Intermediate weathering grade of IV and III

Berm 4 – Weathering grade III

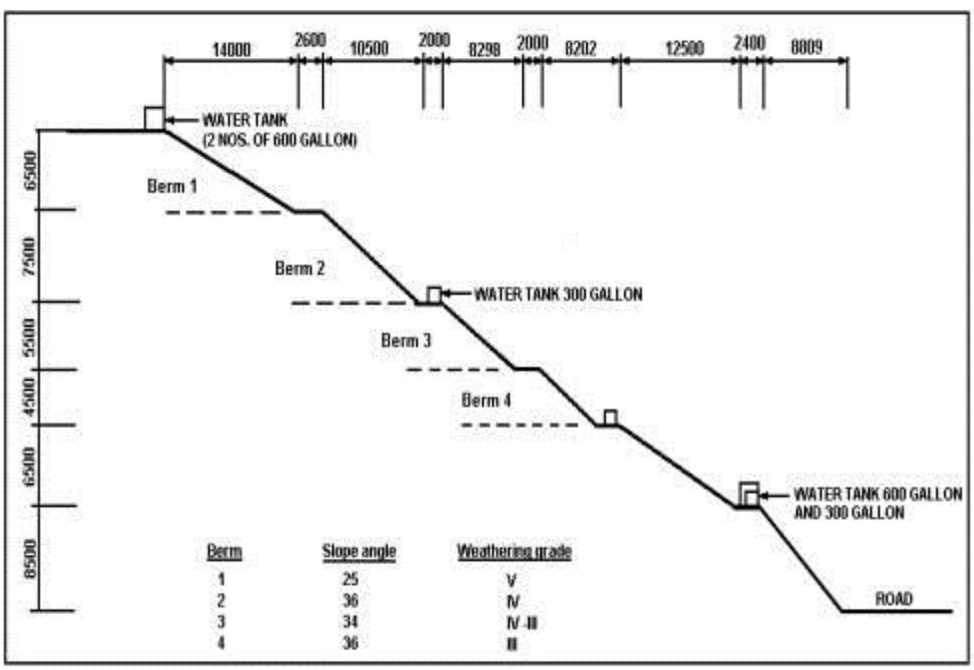

Figure 1. Sectional profile of the cut slope

In order to have a better control of the timing as well as intensity of the rain, as oppose to the unpredictable nature (in term of time, intensity and duration) of natural rain, an artificial rain simulation system using a sprinkler method was designed and setup in the field. The rain simulator system was designed to provide continuous artificial rain during the course of the study.

A 122.4 mm/hour (3.4×10^{-5} m/s) rainfall was the highest recorded rainfall in five years (1995 – 2000) at the Subang Station by the Metrological Department of Malaysia, which was close to the field site, for the 1st hour rain. The rain simulator was designed to impart the same intensity of rainfall for duration of 150 minutes (2 ½ hours). The rain simulator system basically comprised of water tanks, pumps and piping systems, sprinklers, flow meters and v–notch collection drains. The sprinkler system comprised of a 15' x 15' sprinkling frame, made of steel tubes, PVC piping and sprinkler heads as shown in Figure 2. Figure 3 shows a rainfall simulation in progress. Note that polythene sheets were used to enclose sides of the sprinkling/catchments area to minimize loss of water and direct surface run off to the collection drain. Figure 4 shows a close up view of the sprinkler head.

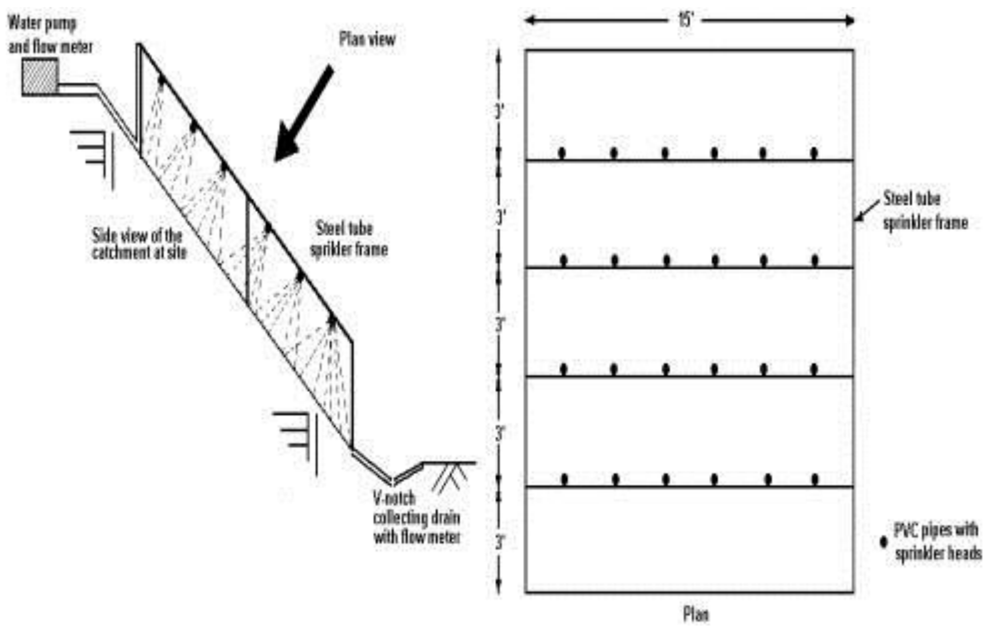

Figure 2. Sprinkling frame and locations of sprinkler heads

Figure 3. Rainfall simulation in progress

Figure 4. Sprinkler head

To monitor the rate of water inflow and to regulate the flow to the test site, flow meters (Figure 5) were installed. This enable the total volume of water supplied to the test locations to be measured. The excess (surface run off) water from the test site was in turn directed the v-notch collection drain, and measured using the flow meter at the outlet. The difference in the inflow and outflow was used to estimate the average rate of water infiltration into the soil.

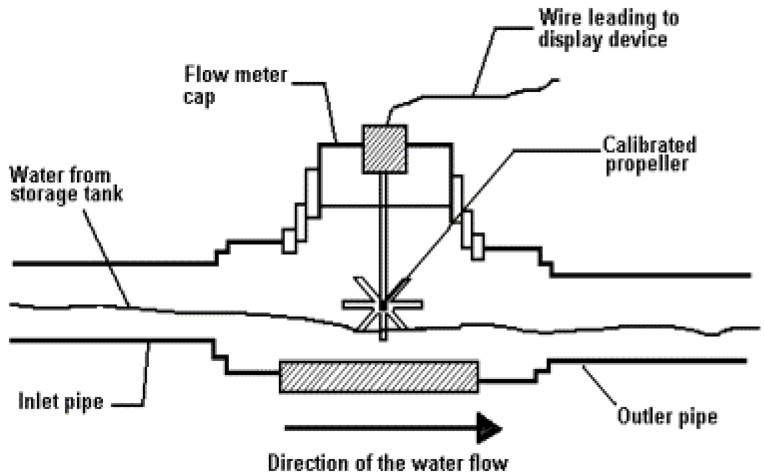

Figure 5. Working concept of a flow water

RESULT AND DISCUSSION

Field Results

The first part of the study was to examine the influence of surface cover on the average infiltration rate of a cut slope in unsaturated residual soil. Six surface conditions were studied as follows.

In case 1, the test was conducted in natural condition where the slope surface was covered with the usual dense grass.

In case 2, the grass was trimmed to 1" high in order to study the effect of a well trimmed and maintained slope surface.

In case 3, the slope surface was trimmed bare, to model the condition of a fresh slope.

In case 4, the slope was covered with geosynthetic net and normal dense grass.

In case 5, the slope had both cover of geosynthetic net and grass, as in case 4, but the grass was trimmed to 1" high.

In case 6, the slope surface was stripped of its grass cover, leaving only the geosynthetic net.

On berms 1 and 2, which fall roughly on soils of weathering grade V and IV, the effect of surface conditions of case 1, 2 and 3 on the water infiltration rate was studied. The results obtained are summarized in Table 2.

Table 2. Average infiltration rate of berms 1 and 2

Berm	Weathering grade	Surface Condition	Average infiltration rate (mm/s)	Berm	Weathering grade	Surface condition	Average infiltration rate (mm/s)
1	V	1. Normal dense grass	0.40×10^{-6}	2	IV	1. Normal dense grass	0.60×10^{-6}
		2. 1” high cut grass	0.80×10^{-6}			2. 1” high cut grass	1.00×10^{-6}
		3. Bare surface	1.20×10^{6}			3. Bare surface	2.30×10^{-6}

From the above table, it appeared that the water infiltration rate into the soil increased from the fully vegetated slope to trimmed slope, and to bare surface. For a particular surface cover, berm 2, which comprised of the grade IV weathered material, had high infiltration rate indicating the more porous nature of the soil material. This was despite the fact that berm 1 was a gentler slope compared with berm 2. Steeper slope angle would enhance surface flow, and thus reduce rate of water infiltration into the slope.

The effect of surface cover on average infiltration rate was studied on berm 3 and 4 for surface conditions of 3, 4, 5 and 6. The results obtained are summarized in Table 3. Both the slopes were roughly of the same angle, between 34 – 36^{o}. These berms fall roughly on soils of weathering grade IV and III.

Table 3. Average infiltration rate of berms 3 and 4

Berm	Weathering grade	Surface Condition	Average infiltration rate (mm/s)	Berm	Weathering grade	Surface condition	Average infiltration rate (mm/s)
3	IV - III	4. Geosynthetic and normal grass	0.70×10^{-6}	4	III	4. Geosynthetic and normal grass	0.90×10^{-6}
		5. Geosynthetic net and 1” cut grass	1.80×10^{-6}			5. Geosynthetic net and 1” cut grass	2.00×10^{-6}
		6. Geosynthetic net only	3.61×10^{-6}			6. Geosynthetic net only	3.01×10^{-6}
		3. Bare surface	4.61×10^{-6}			3. Bare surface	6.91×10^{-6}

From the above table, it appeared that the soil infiltration rate increased from the fully vegetated slope with geosynthetic net, to cut grass slope with geosynthetic net, to geosynthetic net, and to bare surface slope only. For a particular surface cover/condition, berm 4, which was of weathered grade III soil material, had higher infiltration rate compared with berm 3, which was of weathered soil of intermediate grade of IV – III. This is also shown in Table 4 when the average infiltration rate of all the four berms, i.e. of four different weathering grades, and for bare surface condition only, are compared.

Table 4. Average infiltration rate of berms 1, 2, 3 and 4 (of bare surface condition only)

Berm 1	Weathering grade	Infiltration rate (mm/s) (bare surface condition)
1	V	1.20×10^{-6}
2	IV	2.30×10^{-6}
3	IV – III	4.61×10^{-6}
4	III	6.91×10^{-6}

Numerical Study

A comparative study was performed to compare factor of safety against slope instability obtained with conventional slope stability analysis with analysis in-cooperating unsaturated soil parameters. Computer software Seep/W was used to perform the seepage analysis coupled with the Slope/W software which was used to perform slope stability analysis using the extended Mohr Coulomb criterion to account for increase in soil strength due to the matric suction (Fredlund and Rahardjo, 1993). Seepage analysis of the cut slope was performed incorporating the measured average rates of infiltration as shown in Tables 2-4, for slopes of the various weathering grades and surface cover. The rain on the slope was simulated as a heavy rainfall (122.4 mm/hour) for duration of 2 ½ hours.

As in the field tests, the following surface covers were considered; slope surface covered with natural grass, slope surface covered with 1" high cut grass, slope surface covered with natural grass and geosynthetic, slope surface covered with 1" high cut grass and geosynthetic, slope surface covered with geosynthetic only, as well as bare slope surface.

Table 5 summarizes the input parameters considered in the analysis, in accordance to the respective weathering grade.

Table 5. Input parameters for soils of various weathering grades

Weathering grade/Berm	Slope cover	Average infiltration rate x 10^{-6} m/s	Cohesion, *c* (kPa)	Angle of friction, ϕ'	Increase in shear strength due to suction, ϕ_b	Unit weight, γ (kN/m^3)
V (Berm 1)	Natural grass	0.40	10	26	26	18
	1" high cut grass	0.80				

	Bare slope	1.20				
IV (Berm 2)	Natural grass	0.60				
	1” high cut grass	1.00	8	28	26	18
	Bare slope	2.30				
IV and III (Berm 3)	Natural grass and geosynthetic	0.70				
	1” high cut grass and geosynthetic	1.80	4	31	24	18
	Geosynthetic only	3.61				
	Bare slope	4.61				
III (Berm 4)	Natural grass and geosynthetic	0.90				
	1” high cut grass and geosynthetic	2.00	0	33	19	18
	Geosynthetic only	3.01				
	Bare slope	6.91				

The results obtained in term of factor of safety with respect to the various cases analyzed are given in Table 6 below.

Table 6. Summary of factor of safety

Description/ Slope cover	Berm → Weathering grade →	Berm 1 V	Berm 2 IV	Berm 3 IV – III	Berm 4 III
Conventional analysis without matric suction		1.592	1.535	1.388	1.204
Analysis incorporating matric suction, prior to simulated rain		2.785	2.330	2.108	1.757
After 2 ½ hrs rain; slope surface covered with natural grass		2.696	2.201	-	-
After 2 ½ hrs rain; slope surface covered with 1” high cut grass		2.523	2.132	-	-
After 2 ½ hrs rain; bare slope surface		2.440	1.978	1.698	1.289
After 2 ½ hrs rain; slope surface covered natural grass and geosynthetic		-	-	1.988	1.574
After 2 ½ hrs rain; slope surface covered with 1” high cut grass and geosynthetic		-	-	1.857	1.458

After 2 ½ hrs rain; slope surface covered with geosynthetic only	-	-	1.731	1.406

The factors of safety obtained from analysis incorporating the matric suction were higher than the factor of safety obtained from the conventional slope stability analysis without matric suction. The differences in factor of safety by incorporating matric suction ranged from 12% to 35% higher as compared to the conventional slope stability analysis.

There was a trend of reduction in factor of safety with rain, in particular for slopes with the lesser cover. As expected the worst condition is for case of bare slope surface.

The higher the soil infiltration rates, as in the case of soil of weathering grade IV and III, the lower were the factors of safety.

CONCLUSION

From the results of the study, the following conclusion can be drawn.

The soil infiltration rate as measured from the field test showed an increase from fully vegetated slope with geosynthetic net, to cut grass slope with geosynthetic net, to geosynthetic net, and to bare surface slope only.

For a particular surface cover/condition, soil of weathering grade III had higher infiltration rate compared soils of intermediate grade (IV – III), grade IV and grade V.

The factor of safety obtained from analysis by incorporating matric suction was much higher than the factor of safety obtained from the conventional slope stability analysis without matric suction.

There was a trend of reduction in factor of safety with rain, in particular for slopes with the lesser cover. As expected the worst condition was for case of bare slope surface.

The higher the soil infiltration rate, as in the case of soil of weathering grade III, the lower was the factor of safety against instability of the slope.

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