Rainfall Infiltration, Soil Matric Suction and Slope Engineering

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ABSTRACT: Unsaturated soil mechanics has undergone tremendous amount of research in both field and laboratory creating new concepts and theories for practicing engineers. The behaviour of unsaturated soil in the field is very sensitive to the flex changes of ground water table and rainfall infiltration. This research paper covers in depth the study of unsaturated residual soil behaviour in both laboratory and field. Various research tools used to measure important data such as matric suction, rainfall records, infiltration rate, surface runoff, unsaturated and saturated soil shear strength and soil moisture characterizes. The research data, compiled to conclude the influence of rainfall infiltration on insitu soil shear strength, drop in matric suction with time and the drop in slope factor of safety. Based on the data analysis and compilation it is found that the soil shear strength and infiltration rate increases with soil weathering grade and soil grain saiz. This have direct influence on the matric suction of soil, the higher the infiltration rate, the higher the rate of matric suction drop during rainfall. The finding shows the need for well covered slope surface to prevent suction induced slope failures. By comparing the actual field data, the rate of changes in suction for bare slope surface is much faster as compared to well-covered slope surface. This paper will present in detail the research test results, related to matric suction both field, and laboratory findings along with rainfall infiltration and drop in slope factor of safety analysis.

KEYWORD : Matrix suction, infiltration, unsaturated, shear strength, surface runoff, slope factor of safety

1 INTRODUCTION

Residual soils in Malaysia commonly originated from weathered igneous, sedimentary or metamorphic rock. The tropical climate of Malaysia with high temperature and rainfall, have continuous cyclic of wet and dry influence on soil weathering, creating various level of weathering grades of insitu rock. The weathered soil mainly described as residual soil with weathering grades ranging between VI to II. Residual soils are very common in hilly areas of Malaysia. However, the sedimentary rocks in Malaysia ranges from firm quartzite sandstone to soft phyllites and shales both of which weathered deeply to give a weathering grade of VI consistency. The cut slopes formed in this material are less stable than those in other sedimentary rocks are as the soil becomes cohesionless with time as pore water pressure dissipates. The soil mechanic behavior of these weathered residual soils going through series of wetting and drying cycle varies from soil type, weathering grades, permeability and vegetation coverage. This variation extends the need to study the saturated and unsaturated mechanics of weathered residual soils.

A better understanding of soil mechanics would mean a better design of slopes in terms of cost and safety. In this regard, numerous test programs were initiated at University of Malaya to study the effect of negative pore water pressure (suction) on properties of partially saturated residual soils. Hence the research was divided into two categories, namely field study and laboratory study.

2 INTRODUCTION OF UNSATURATED SOIL MECHANICS

The principal and fundamental research on unsaturated soil mechanics started in 1962 by Jennings and Burland of Imperial College. At that time much interest was given on Terzaghi's (1936) principle of effective stress for saturated soil, which was proposed by him in the first International Conference on Soil Mechanics in 1936. The concept and research interest on unsaturated soil mechanics developed only in 1977. Fredlund and Morgenstern made the revitalization of unsaturated soil mechanics possible. Fredlund and Morgenstern introduced the third factor of $(U_a - U_w)$ into the earlier equation of effective stress defined as (Bishop, 1959).

$$\sigma' = (\sigma - U_w) + X\,(U_a - U_w) \qquad \text{equation 1}$$

Where σ′ and σ are the effective and total stress respectively, U_a is the pore air pressure and U_w is the pore water pressure. X is a function that depends on the saturation values which ranges between 1 to 100% and 0% for completely dry soil. The relationship between X and saturation is determined experimentally to evaluate the strength. τ , written in terms of stress state variables for an unsaturated soil is an extension of equation used for saturated soils (Glenn O, Schwab and Rizhard K. Frevert).

$\tau = c' + (\sigma - U_a)) \tan \phi' + (U_a - U_w) \tan \phi^b$ equation 2

where:

c' = Effective cohesion
σ = Total stress
U_a = Pore air pressure
ϕ' = Effective angle of internal friction
U_w = Pore water pressure
$(U_a - U_w)$ = Matric suction
ϕ^b = Angle indicating the rate of increase in shear strength with respect to changes in $(U_a - U_w)$ when $(\sigma - U_w)$ is held constant.

The above equation assumes a planer failure envelope, the internal friction angle ϕ' , remains essentially constant under saturated and unsaturated condition (Bishop, 1959). The angle ϕ^b, which quantifies the effect of suction, is measured from the τ v_s $(U_a - U_w)$ plot. The cohesion intercepts at C_1, C_2 and C_3 due to the applied suction $(U_a - U_w)$ which varies if the angle of internal friction ϕ' remains constant for different suction levels (Burland, 1964). Figure 1.0 shows the matric suction drawn on a failure envelope.

3 LABORATORY AND FIELD WORKS

The research site from where the soil samples were taken is situated on a slope along the airport link road in the district of Sepang. Public Works Department of Malaysia (JKR) granted the site for research purposes. The site comprises of about 30m ~ 40m high cut slope with the link road built at the toe. The schematic drawing of sectional profile of the cut slope is shown in Figure 2.0.

Studying and understanding the research site is a crucial aspect of this research. It was important to understand the soil conditions at the research location. Hence a comprehensive site investigation was performed involving site geological mapping, insitu block sampling (Brand E. W. and Phillipson H. B., 1985), boreholes and standpipes. The samples collected from site were then extruded and categorized into the respective weathering grades before soil shear strength or soil-moisture characteristic studies were done.

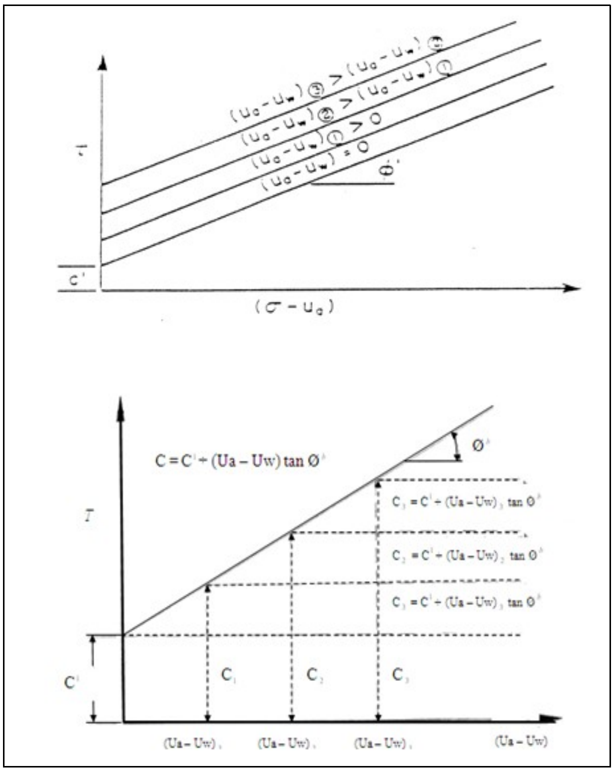

Figure 1.0 : Matric suction drawn on a failure envelope

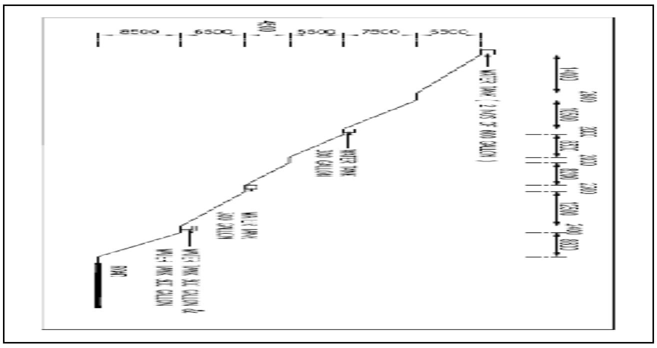

Figure 2.0 : Sectional profile of the cut slope

The cut slope of approximately 30m ~ 35m high was exposed to soil weathering grades of VI, V, IV, III and II. The soil weathering grades can influence the following soil parameters.

a) Infiltration or permeability of soil
b) Shear strength of saturated and unsaturated soil.
c) Hysteresis of soil during wetting and drying for various weathering grades
d) Rate of matrix suction changes with rainfall infiltration
e) Soil erosion rate

The cut slope was mapped for the weathering grades. The weathering grades were categorized based on description given by the Geological Society of Engineering Group, Working Party Report (Robert B. Johnson and Jerome V. Degraff).

The soils shear strength determinations for the proposed site were sub divided into four soil weathering grades. The soil samples were collected with reference made to the geological map and weathering grades. Shear strength tests were carried out for the following weathering zone:

1) Weathering grade V, located at Berm 1
2) Weathering grade IV, located at Berm 2
3) Intermediate weathering grade IV and III, located at Berm 3
4) Weathering grade III, located at Berm 4

The summary of soil effective shear strength are tabulated in Table 1.0:

Case	Description	Effective Cohesion C' (kPa)	Effective Friction Angle ϕ'
1.	Weathering Grade V – Berm 1	10	26^0
2.	Weathering Grade IV – Berm 2	8	28^0
3.	Intermediate Weathering Grade IV to III – Berm 3	4	31^0
4.	Weathering Grade III - Berm 4	0	33^0

Table 1.0 : CIU test results

The test results indicate a constant increase in effective friction angle (ϕ') and drop in effective cohesion (C') as the weathering grades increases. Consistent with particle size distribution finer particles at grade V weathering zone provide higher cohesion, and lower friction angle as compared to grade III material, which is much coarser.

3.1 UNSATURATED TRIAXIAL TEST RESULTS

The samples used for unsaturated triaxial test were obtained from the same block sample, used to retrieve samples for CIU triaxial test and soil-water characteristic test. Retrieving samples, from the same block sample, will minimize the soil sample variation and increase the test result accuracy. Example test result of unsaturated multistage triaxial test for berm 1 sample are tabulated in Table 2.0.

From the test findings, it clearly indicates that the shear strength of the soil reduces for all suction level as the weathering grade changes from grade V to grade III. Relative to shear strength the value of ϕ^b also reduces as the change in weathering grade takes place. The influence of matric suctions are much greater for soils of weathering grades of V and VI. As compared to soils of weathering grade IV and III this is due to the less cohesive and much permeable soil is present at soils of weathering grade IV and III.

Sample at Berm I – Summary of Test Results Weathering Grade V

Suction (kPa)	Shear Strength (kPa)	ϕ^b
0	10	36
50	60	
100	82	
200	95	
300	97	

Table 2.0 : Berm 1 unsaturated multistage triaxial test results

3.2 SOIL WATER CHARACTERISTICS DETERMINATION FOR UNSATURATED SOIL

The moisture suction relationships of soils are not unique and the relationship depends on the condition of the soil either on wetting or drying state. The wetting and drying curves in the relationship shows a hysteresis variation with numerous scanning curves in between the two boundaries of wetting and drying curves.

This study is to observe the changes in soil suction with water content for both laboratory and field. In the laboratory the study was carried out using Modified Rowe Cell by introducing matric suction using axis translation technique. The in-situ values at the field were determined using quick draw tensiometers. A correlation is then obtained between the laboratory and in-situ field test results.

Field and laboratory tests were performed for the study using quickdraw tensiometer to determine soil water characteristic relationship in the field, whilst Modified Rowe Cell was used for the laboratory test. Figure 3.0 indicate the combination plot of field and laboratory soil-water characteristic curve for samples at berm 1. The match points between field and laboratory results are not identical, especially for suction value higher then 50 kPa. However the field and laboratory, soil water characteristic curves, converge at lower suction and diverge when the matric suction increases. The smooth transition point is need to be identified when both the data are combined

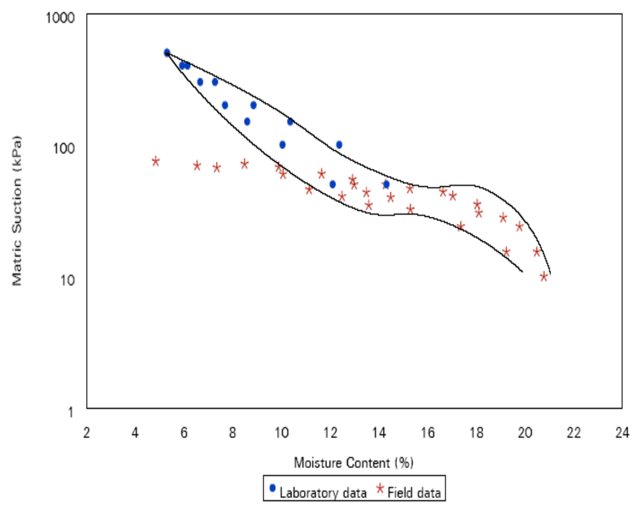

Figure 3.0 : Combination of Field and Laboratory Soil-Water Characteristic Curve Berm 1

3.3 FIELD INSTRUMENTATION AND MONITORING

In order to study the influence of rainfall on soil infiltration rate and rate of soil suction changes with time due to infiltration. An artificial rainfall simulation system using sprinkler method was setup in the field. The sprinkler system was designed to provide continuous artificial rainfall during the experiment. The area within the sprinkler system was well instrumented to measure the suction changes with time during rainfall. The test was conducted for the four various soil weathering grades as described in previous chapters. At every test location the experiments were categorized into the tabulated surface condition.

The tests were required to study soil suction changes with heavy rainfall that were maintained for two and half-hours with intensity of 122.4mm/hour. The 122.4mm/hour rainfall was the highest recorded rainfall within the test site area. Schematic drawing of the experiment setup is shown in Figure 4.0. Description to test conditions are tabulated in Table 3.0.

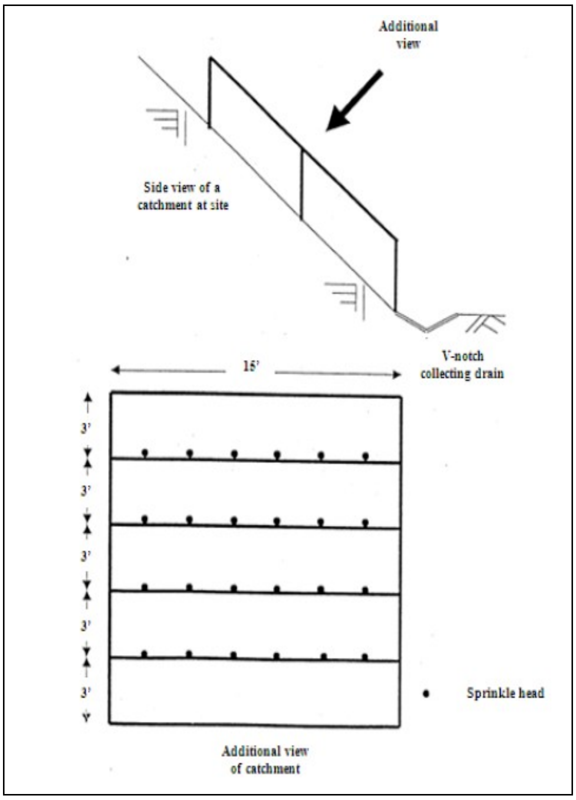

Figure 4.0 : Illustrates the sprinkling frame and sprinkler locations

4.0 SLOPE STABILITY WITH RAINFALL AND MATRIC SUCTION INCOPERATION

By incooperating field and laboratory data, slope stability analysis were carried out to understand the influence of rainfall, infiltration, matric suction and slope surface cover on slope factor of safety.

From the analysis carried out, the summarized list of factors of safety with respect to the various cases analysized are given belowe in Table 4.0.

Case	Description
1	The experiment was conducted in natural condition of the slope surface, which was covered with normally dense grass to study the natural occurrences of rainfall infiltration into slope.
2	The slope surface of natural grass was trimmed to 1″ high grass to study the condition of well trimmed and maintained slope surface
3	Under this condition the slope surface was trimmed bare to model the condition at fresh slope surface
4	Slopes under weathering grades of III and IV were covered with geosynthectic and grass to prevent erosion. Under this case the combination of natural grass and geosynthectic on slope surface was studied.
5	The slope surface was covered with natural grass and geosynthectic and the grass was trimmed to 1″ to study the influence of geosynthetic on well maintained slope surface
6	Under this condition the grass was removed and slope surface was left with geosynthectic only.

Table 3.0: Description of test conditions

By analyzing the above factors of safety there is a trend of reduction in factors of safety with rainfall from the initial insitu condition in case 3 before rainfall to case 3–I of slope covered with natural grass. However by exposing the slope surface to rainfall it is observed that, there is a sudden or drastic drop in factor of safety between 3% to 10% from the insitu slope matric suction condition in case 3 as compared to condition where the slope surface is exposed to rainfall as analyzed in case 3-I and 3-IV.

By further exposing the surface, to the worst condition of bare slope surface, the percentage of drop in factor of safety from initial insitu condition in case 3 to bare slope condition is between 12% to 20%.

However as compared to the worst condition of bare slope surface, the stability analysis by incorporating matric suction, the slope factor of safety obtained is much higher than the factor of safety obtained by not incorporating matric suction (conventional slope stability analysis). The differences in factor of safety by incorporating matric suction ranges between 12% to 35% higher as compared to conventional slope stability analysis.

Case and Subcase	**Descriptio of slope condition**		**Berm 1**	**Berm 2**	**Berm 3**	**Berm 4**
		Subcase	**A**	**B**	**C**	**D**
2	Conventional analysis		1.592	1.535	1.388	1.204
3	Insitu condition with matric suction		2.785	2.330	2.108	1.757
3-I	Slope surface covered with natural grass		2.696	2.201	-	-
3-II	Slope surface covered with 1" high cut grass		2.523	2.132	-	-
3-III	Bare slope surface		2.440	1.978	1.698	1.289
3-IV	Slope surface covered natural grass and geosyntectic		-	-	1.988	1.574
3-V	Slope surface covered with 1" high cut grass and geosyntectic		-	-	1.857	1.458
3-VI	Slope surface covered with geosyntectic only		-	-	1.731	1.406

Table 4.0 : Summary of factor of safety for various cases

The wide differences of 15% and 35% in factor of safety is recorded for cases under berm 4 and berm 1 respectively. It is understood that the infiltration rate in berm 4 is much higher then berm 1. Therefore as the infiltration gets higher, the influencing factors of matric suction become insignificant under prolonged rainfall. It is crucial to maintain well-vegetated slope surface on highly infiltrable slope surface.

The above observation is possible as the failure plane for the analysis is uniformized in order to observe the drop in factor of safety for a particular failure plane. The analysis not necessarily gives the lowest factor of safety under each case. It is also observed that the factors of safety under case 2 (conventional analysis) reduces from berm 1 to berm 4. This drop is due to reduction in effective cohesion in the weathered sandstone material as the weathering grades reduces and the material become more granular. However there is an net increase in effective friction angle with weathering grade as the material become more granular as shown in Table 1.0.

Figure 5.0 and 6.0 shows the seepage model for slope surface cover with grass and bare slope condition respectively. Figure 7.0 shows the typical slope stability analysis carried out incooperating seepage model for bare slope surface condition for weathering grade v.

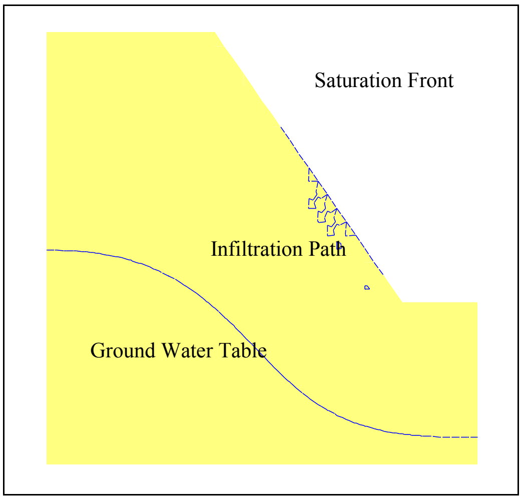

Figure 5.0: Seep model showing infiltration of rainwater weathering grade V slope surface covered with natural grass

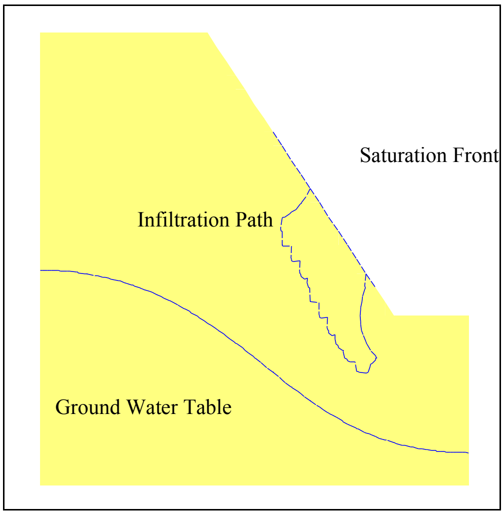

Figure 6.0: Seep Analysis Model showing infiltration of rainwater on weathering grade V. Bare slope surface condition

5 RESULTS AND DISCUSSIONS

Based on the geological formation the cut slope profile falls under the following weathering grades

a) Berm 1 – Weathering grade V
b) Berm 2 – Weathering grade IV
c) Berm 3 – Intermediate weathering grade of IV and III
d) Berm 4 – Weathering grade III

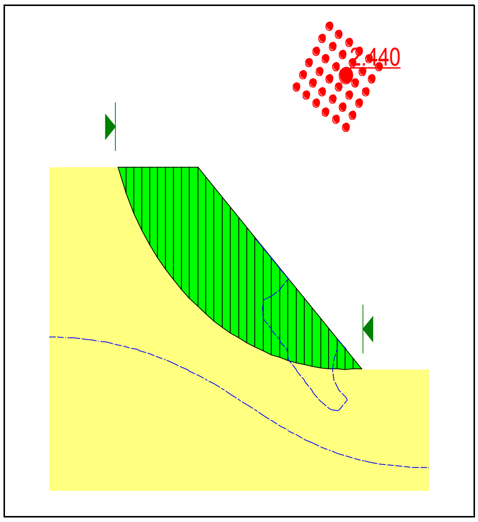

Figure 7.0: Shows the stability analysis carried out incooperating seepage model for bare slope surface weathering grade V

Therefore the experiments were subdivided into the respective soil weathering grades.

i) Berm 1 and 2 - which falls on weathering grade of V and IV were grouped to perform the following test
   - Case 1 – The slope surface was covered with natural grass.
   - Case 2 – The slope surface was covered with 1″ high cut grass.
   - Case 3 - Bare slope surface.

ii) Berm 3 and 4 – which falls on weathering grade of III and IV was grouped to perform the following test
   - Case 4 – The slope surface was covered with natural grass and Geosyntectic.
   - Case 5 – The slope surface was covered with 1″ high cut grass and Geosyntectic.
   - Case 6 – The slope surface was covered with geosynthectic only.
   - Case 3 - Bare slope surface

Example plot of matric suction changes with time during the experiment are presented in Figures 8.0 for case 3 at berm 4 is shown.

By studying the behavior of matric suction changes during rainfall for the test it is found that the trend of suction changes is relatively consistent with time. The results exhibits an immediate increase in matric suction within the first 20 minutes of rainfall before a gradual drop in suction take place. The consistent drop in suction illustrates the effect of net infiltration process taking place only after 20 minutes of rainfall. However with constant rainfall for the next 130 minutes a clear drop in soil suction is observed. Indicating the trend of suction changing with time in the field during rainfall.

At 150 minutes the artificial rainfall is stopped and a sudden drop in suction is observed. In some cases the suction continues to drop further about 15 kPa to 25 kPa. This continues drop after rainfall is observed in all the small tip tensiometer and shallow jet fill tensiometer. After the rainfall is stopped at 150 minutes, the suction continue to drop further at much higher rate for the next 30 minutes as compared to the rate of suction drop during rainfall. The drop in suction at much higher rate continuous until suction stabilization take place and drying process begins.

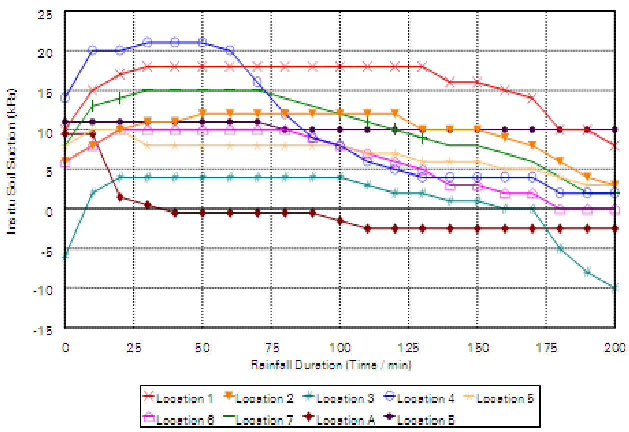

Figure 8.0 : Berm 4 - Case 3 : - Bare Slope Surface Insitu Soil Suction Vrs Rainfall Duration

The sudden increase of matric suction at the beginning of rainfall and sudden drop in matric suction after rainfall, is believed to be caused by lamina flow of rainwater at the slope surface. The flow creates lower pressure zone at the surface, which respectively increases the soil matric suction. However a sudden stop of, rainwater flow releases the low pressure zone at the surface, causing an immediate drop in soil suction as the surface water rushes into the ground. The phenomenon also increases the water infiltration rate into the slope, causing an accelerated drop in suction or increase in positive pore water pressure immediately after rainfall. From the study, the computed soil infiltration rate for all the test condition for the respective weathering grades are listed in Table 4.0

Weathering Grade	C	Surface Cover	Infiltration Rate (m/s)
V	I	Slope surface covered with natural grass	4.01×10^{-7}
	II	Slope surface covered with 1″ high cut grass	8.02×10^{-7}
	III	Bare slope surface	1.20×10^{-6}
IV	I	Slope surface covered with natural grass	6.01×10^{-7}
	II	Slope surface covered with 1″ high cut grass	1.00×10^{-6}
	III	Bare slope surface	2.30×10^{-6}
IV	IV	Slope surface covered with natural grass and geosynthectic	7.01×10^{-7}
	V	Slope surface covered with1″ high cut grass and geosynthectic	1.80×10^{-6}
	VI	Slope surface covered with geosynthectic only	3.61×10^{-6}
	III	Bare slope surface	4.61×10^{-6}
III	IV	Slope surface covered with natural grass and geosynthectic	9.02×10^{-7}
	V	Slope surface covered with1″ high cut grass and geosynthectic	2.00×10^{-6}
	VI	Slope surface covered with geosynthectic only	3.01×10^{-6}
	III	Bare slope surface	6.91×10^{-6}

Table 4.0 : Infiltration rate for various weathering grades and soil surface condition

A consistent pattern of increase in infiltration rate is recorded as the slope surface is exposed to rainfall. From the above tables the following points can be derived.

i) The infiltration increases as the slope surface exposed to rainfall by means of surface clearances from fully vegetated slope to bare slope surface.
ii) Infiltration rate increases as soil-weathering grade reduces from grade V to grade III. This is due to the increase in grain size from weathering grade V to III.
iii) In any slope design the surface runoff on slope surface need to be minimized as the phenomenon of sudden drop in matric suction after rainfall can trigger minor facial failures or deep-seated failure in highly permeable soils.
iv) It is recommended to have good vegetation on slope surface to minimize surface infiltration during rainfall. Close turfing and tree planting is recommended.
v) The slope surface is required to be protected by providing sufficient drainage system, to intercept surface runoff by means of berm drain and interceptor drains.
vi) However proper maintenance of drainage system is also crucial, to avoid blockage and leakage which could enhance the infiltration rate.

6 CONCLUSIONS

Some fundamental aspects of unsaturated soil mechanics have been studied using field instrumentation and laboratory experiment. The field and laboratory data are interrelated to investigate the influencing factors of unsaturated soil mechanics on slope stability and its factor of safety. From this research the factors influencing matric suction in slopes are found to be:-

i) The soil weathering grades.
ii) Soil shear strength and ϕ^b .
iii) Slope surface conditions.

6.1 WEATHERING GRADES AND SOIL SHEAR STRENGTH

Based on the geological mapping the selected sandstone weathering grades of V, IV, intermediate grade between IV and III, and III was selected for research.

The samples collected from the said weathering profile were tested for their effective cohesion and effective friction angle, using conventional triaxial set and modified triaxial set by in cooperating multiple suction values to obtain ϕ^b (the rate of increment in shear strength with respect to changes in matric suction when effective stress was held constant). The summary of laboratory data obtained are shown in Table 5.0.

Weathering Grade	Effective Cohesion c’ (kPa)	Effective Friction Angle ϕ’ (deg)	ϕ^b
V	10	26	36
IV	8	28	26
IV and III	4	31	24
III	0	33	19

Table 5.0: Summary of soil parameters

From the above table the soil effective friction angle increases consistently with weathering grade. However the effective cohesion and ϕ^b trend to reduce as the weathering grade reduces. This is due to the increment in non-cohesive material of sand at weathering grade III material. The grain size increases from weathering grade V to III. At weathering grade V the much clayey and silty material dominated the shear strength properties by giving higher effective cohesion and indirectly higher ϕ^b value. However at weathering grade of III the much sandy material gives very low effective cohesion and much reduced ϕ^b value as compared to weathering grade V. It can be conclude that the ϕ^b value is dominated by the soil cohesion as compared to effective friction angle.

6.2 SLOPE SURFACE COVER AND INFILTRATION RATE

Based on the intensive research carried out at the field to investigate the influence of soil surface cover and infiltration rate with respect to weathering grade, following conclusion can be obtained

i) A trend of increment in infiltration rate as the slope surface was exposed to rainfall.
ii) Approximately 3 to 4 times of infiltration increment were recorded between slope surface covered with natural grass and bare slope surface for weathering grade V and IV.
iii) However for weathering grade between IV and III, and grade III the recorded infiltration

increment between slope surface covered with natural grass and geosynthectic, and bare slope surface is between 6.5 to 7.5 times.

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