Analysis of Infiltration-Suction Response in Unsaturated Residual Soil Slope in Gelugor, Penang

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Abstract. Rainfall infiltration on residual soil slope may impair slope stability by altering the pore-water pressure in the soil. A study has been carried out on unsaturated residual soil slope in Gelugor, Penang to determine the changes in matric suction of residual soils at different depth due to rainwater infiltration. The sequence of this study includes the site investigation, field instrumentation, laboratory experiment and numerical modeling. Void ratio and porosity of soil were found to be decreasing with depth while the bulk density and dry density of soil increased due to lower porosity of soil at greater depth. Soil infiltration rate and matric suction of all depths decrease with the increase of volumetric water content as well as the degree of saturation. Numerical modeling was used to verify and predict the relationship between infiltration-suction response and degree of saturation. Numerical models can be used to integrate the rainfall scenarios into quantitative landslide hazard assessments. Thus, development plans and mitigation measures can be designed for estimated impacts from hazard assessments based on collected data.

1. Introduction

Classical groundwater detection instrument thru drilling method experienced several limitations due to Soils located above groundwater table are normally unsaturated soil and possess negative pore-water pressure. An unsaturated soil is commonly defined as having four phases: 1) solids, 2) water, 3) air and 4) contractile skin [11]. The natural hydrologic cycles influence the water content and negative pore water pressure of the soil. Infiltration of rainwater reduces matric suction of the soil which then decreases the soil shear strength, and subsequently triggers the slope failure [8]. The stability of slopes has become a major concerning issue in tropical regions that experience frequent periods of heavy downpours. Hence, it is important to investigate the response of unsaturated residual soil slope due to rainfall such as the changes in soil matric suction. The soils that undergo the weathering process without being transported are called residual soil. The variation of engineering properties can be seen in residual soil from top layer to bottom layer. Relatively finer materials are found near ground surface and they become coarser with depth to reach larger fragment of stone. In recent years, residual soils have become
a particular concern due to the primary factor of negative pore water pressure that causes unusual behavior of the soil.

Previous studies have proven that rainfall has a destructive effect on the stability of residual soil slopes [13]. This is due to the loss of additional shear strength that is present in unsaturated soils provided by negative pore-water pressures as a result of rainwater infiltration into the soil. When rainwater falls on the surface of a slope, some of the water flows down the slope surface as surface runoff and some water infiltrates into the ground. The rate of infiltration takes place depends on several factors such as precipitation, land cover, soil saturation, soil characteristics and the slope of the land [23]. As rain water infiltrates into soil slope, it increases the moisture content, causing a reduction of the suction which making the pore pressures less negative hence lowering the shear strengths of the soil [24].

The objective of this study is to investigate the response of residual soil subjected to rainwater infiltration. The changes in matric suction and water content at different depth of the residual soil were monitored during infiltration. From this study, the relationship between infiltration-suction response and degree of saturation can be developed.

2. Mechanism of an Unsaturated Soil

2.1 Rainwater infiltration through an unsaturated soil

The flow of water through a saturated or unsaturated soil can be described by Darcy’s law [7]:

\[ v_w = -k_w \frac{\partial h_w}{\partial y} \]  

where: \( v_w \) = flow rate of water; \( k_w \) = coefficient of permeability with respect to the water phase; \( \frac{\partial h_w}{\partial y} \) = hydraulic head gradient in the y-direction designated as \( i_{wy} \).

For a saturated soil, the coefficient of permeability, \( k_w \) is constant which is equal to the saturated coefficient of permeability, \( k_s \). The \( k_w \) value of the unsaturated soil is not a constant but is a function of the matric suction \((u_a-u_w)\) of the soil [20]. When the soil saturated, the value of \( k_w \) is equal to \( k_s \) while the value of \( k_w \) becomes less than \( k_s \) when the soil desaturates. The values of \( k_w \) can decrease significantly with an increasing matric suction \((u_a-u_w)\). The decreasing coefficient of permeability when soil desaturates is referred to the permeability function.

2.2 Shear strength of an unsaturated soil

The independent stress state variables as follows expressed the shear strength of an unsaturated soil [12], [15]:

\[ \tau_\phi = c' + (\sigma_f - u_w) \tan \phi' + (u_a - u_w) \tan \phi_b \]

where: \( \tau_\phi \) = shear stress on the failure plaine at failure; \( c' \) = effective coefficient which is the intercept of the extended Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction are equal to zero; \( (\sigma_f - u_w)_f \) = net normal stress at failure; \( (u_a - u_w)_f \) = matric suction at
failure; $\varphi^*$ = angle of internal friction associated with the net normal stress $(\sigma_f - u_a)$; and $\varphi^b$ = an angle indicating the rate of increase in shear strength relative to matric suction, $(u_a - u_w)$.  

The extended Mohr-Coulomb failure envelope is defined as a three-dimensional surface tangent to the Mohr circles at failure with the shear stress, $\tau$, as the ordinate and the two stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$ as abscissas [20].

3. Soil Sampling and Laboratory Testing

Beneficial results of a soil test depend on a good sample. The sample should represent the area of which it is taken from. A soil sample must be taken at the right time and in the right way. The tools used, area sampled, depth and uniformity of the sample, information provided, and packaging influence the quality of the sample. The sampled material was transported to the laboratory for performing tests to obtain required soil parameters. After weighing and drying, the density and soil moisture content was determined. Excavation of pit was done with four layers at 0.25m each layer. One sample was taken from each of the layers for laboratory tests.

3.1 Atterberg limit

Atterberg limit test was conducted in accordance to determine the consistency of the soil [2]. The upper or liquid limit is the point at which soil behavior changes from liquid to plastic state [16] whereas the lower or plastic limit is the water content at which the transition from plastic to semisolid state suddenly occurs, as discussed by [4], [14], [16] and [17]. Table 1(a) and (b) shows the results of liquid and plastic limits of the soil from different depth respectively. The results showed that the liquid limit and plastic limit have small variation and gradual increment with depth. Plasticity index (PI) is the range of water content over which a soil behaves plastically. As the degree of weathering decreases, plasticity index of residual soils also decreases with depth. The results of the soil plasticity index with depth are summarized in Table 1(c). The decreasing trend could be due to the weathering effect of the soil profiles at this particular site.

| Depth (m) | Liquid Limit (%) |
|-----------|------------------|
| 0.0-0.25  | 50.8             |
| 0.25-0.5  | 52.6             |
| 0.5-0.75  | 54.6             |
| 0.75-1.0  | 56.4             |

(a)

| Depth (m) | Plastic Limit (%) |
|-----------|-------------------|
| 0.0-0.25  | 34.8              |

Table 1. Summary of (a) liquid limits; (b) plastic limits; and (c) plasticity index of soil from different depth.
3.2 Particle size distribution
The particle size analysis test was carried out to classify and determine the particle size distribution [1]. The mechanical or sieve analysis was performed to determine the distribution of the coarser, larger sized particle (retained on sieve size 63μm) while the hydrometer analysis was carried out to determine the distribution of the finer particles (passing sieve size 63μm).

The result of particle size distribution for soil sample at different depth was illustrated in Figure 1. Based on Unified Soil Classification System (USCS), results obtained shows that the soil was coarse grained soil because more than 50% of soil was retained on the sieve No. 200 (0.075mm). There was more than 50% soil passes the sieve No. 4(4.75mm), therefore the coarse-grained soil was classified as sands type. As the uniformity coefficient ($Cu$) was higher than 6 and the coefficient of gradation ($Cc$) less than 3, the soil sample can be concluded as the poorly graded sand (SP).

![Figure 1. Particle size distribution for soil sample at different depth.](image-url)
3.3 Specific gravity
Specific gravity test was conducted to determine the specific gravity of the soil [3]. The results of specific gravity for the soil at different depth were presented in Table 2.

| Depth (m) | Specific Gravity |
|-----------|------------------|
| 0.0-0.25  | 2.44             |
| 0.25-0.5  | 2.36             |
| 0.5-0.75  | 2.33             |
| 0.75-1.0  | 2.39             |

Specific gravity is dependent on the mineralogy of a soil and it can reflect the history of weathering [25]. The parent rocks and weathering process are the major factors that alter the mineralogy of residual soils [21].

3.4 Void ratio and porosity
In tropic region, residual soils are weathering product of rocks that are commonly found under unsaturated condition [22]. The void ratio and porosity of the soil sample were found to be decreasing with depth. Table 3 shows the results of the void ratio and porosity of the soil respectively.

| Depth (m) | Void Ratio | Porosity (%) |
|-----------|------------|--------------|
| 0.0-0.25  | 0.8        | 44           |
| 0.25-0.5  | 0.58       | 37           |
| 0.5-0.75  | 0.53       | 34           |
| 0.75-1.0  | 0.51       | 33           |

At the upper layers of residual soils, the weathering process leads the soils to become porous structure due to the leaching of minerals [21]. Water and air replaced the minerals resulting in the porous structure. This is why the upper layers have higher void ratio and porosity compare to the lower layers. Therefore, the void and porosity eventually decreases with depth due to a denser structure at the lower layers.

3.5 Bulk density and dry density
At the upper layers of residual soil, void ratio and porosity were very high. Water and air phase occupy more space compared to the lower layers. As a result, bulk density and dry density are lower when near the surface as shown in Table 4.
Table 4. Summary of bulk density and dry density of soil from different depth.

| Depth (m) | Bulk Density (x10^3 kg/m^3) | Dry Density (x10^3 kg/m^3) |
|-----------|-----------------------------|---------------------------|
| 0.0-0.25  | 1.61                        | 1.33                      |
| 0.25-0.5  | 1.75                        | 1.42                      |
| 0.5-0.75  | 1.85                        | 1.53                      |
| 0.75-1.0  | 1.96                        | 1.67                      |

Therefore, the variation in bulk density as well as the variation in dry density reflects the variation in the degree of weathering.

3.6 Saturated hydraulic conductivity and matrix flux potential

The ability of soil to transmit water subjected to the hydraulic gradient can be measured through saturated hydraulic conductivity and matrix flux potential by using double ring infiltrometer method (as shown in Figure 4). Measurement using this method can be taken at depths up to 4m [9]. In order to obtain a good estimate of both saturated and unsaturated components, the past studies suggested that measurements of just one steady flow rate from a single location are sufficient. The results of the saturated hydraulic conductivity and matrix flux potential were summarized in Table 5.

Table 5. Summary of saturated hydraulic conductivity and matric flux potential of soil from different depth.

| Depth (m) | Saturated Hydraulic Conductivity x10^-6 (m/s) | Matric Flux Potential x10^-3 (cm²/min) |
|-----------|---------------------------------------------|---------------------------------------|
| 0.0-0.25  | 2.83                                        | 1.36                                  |
| 0.25-0.5  | 3.54                                        | 1.95                                  |
| 0.5-0.75  | 2.12                                        | 1.77                                  |
| 0.75-1.0  | 0.71                                        | 0.59                                  |

Results for both saturated hydraulic conductivity and matrix flux potential appear to be higher at the depth of 0.25m-0.5m compared to the other. These happen due to the smaller pore-sizes, lower in coefficient of uniformity and curvature in the residual soils at that depth.

4. Methodology

4.1 Site investigation

Penang Island is mainly underlain by granite as illustrated in Figure 2. Therefore, residual soils formed in situ by weathering of these granite rocks are granitic in nature. A slope in Gelugor, Penang was selected for the case study as depicted in Figure 2. The study area is located on the south eastern area of Penang Island. This area is underlain by medium to coarse-grained biotite granite layer with microcline granite as indicated in the geological map. The orientation of the Gelugor valley is along north-south direction.
4.2 Physical modelling
Laboratory physical modelling was conducted to simulate the on-site condition of Gelugor slope. Soil samples were filled into the PVC acrylic cube measuring at 1m depth, 1m square and 1m height as illustrated in Figure 3. Figure 4 shows the double ring infiltrometer and the actual instrumentations for the physical model. Double ring infiltrometer was used to measure the infiltration rate while tensiometer and time domain reflectometry (TDR) were used to monitor the matric suction and volumetric water content during the experiment.
Figure 3. Soil suction test using tensiometer and time domain reflectometry (TDR).

The TDR model used in this study is Trime-Pico 32 developed by IMKO Micromodultechnik GmbH while the tensiometer model used is the 2100F Soil moisture Probe developed by Soilmoisture Equipment Corporation. The Trime-Pico 32 TDR measures dielectric constant of material to determine the volumetric moisture content. The dielectric constant is a complex quantity with a real number that characterizes the moisture content and with an imaginary component as a measure for energy loss and electrical conductivity. Both parts depend mainly on frequency, so that the measuring frequency of an electromagnetic technique is a decisive criterion. The Trime-Pico 32 TDR rod was placed into the soil and it was connected to the datalogger before attached to the computer using the cable. The measurement from the Trime-Pico TDR directly recorded in computer.

A tensiometer consists of a vacuum dial gauge connected to a plastic body tube and a plastic pipe was used to attach with porous ceramic tip. The tube is normally transparent so when it is filled with the water the water level within it can be seen easily. The porous ceramic tip is permeable, and the water in the tube saturates it. When the tip is placed in the soil, water from the tip will draw into the soil because soil was normally unsaturated. As water seeps into the soil, the gauge starts to measure a partial vacuum. When the soil nearly achieved saturated state, the suction of water into the soil will be close to zero. As long as air does not enter the body tube, the tensiometer reading is accurate. Unlike water, air readily expands and contracts as pressure changes, and air in the tensiometer tube causes inaccurate measurements. Even if the instrument does not have any leak, during normal operation air dissolved in the water accumulates. Therefore, to prevent these from happen the air must be removed periodically by refilling the tensiometer with water.
4.3 Numerical modelling

The numerical modeling was performed using the saturated-unsaturated seepage finite element code named SEEP/W (Geostudio, 2007). In slope stability, seepage analyses may form an important part of studies. The computation of the rate and direction of water flow and the pore water pressure distribution within the flow regime were involved in seepage analyses. The flow of water in the saturated zone has been the primary concern in conventional seepage analyses. According to the recent studies, between the saturated and unsaturated zones there is a continuous flow of water [13], [19].

\[
\frac{\partial}{\partial x}[k_{wx}(\partial h_{w}/\partial x)+k_{wxy}(\partial h_{w}/\partial y)]+\frac{\partial}{\partial y}[k_{wy}(\partial h_{w}/\partial y)] = m_{w}^{2} \rho_{w} g (\partial h_{w}/\partial t)
\]  

(3)

where: \(k_{wx}, k_{wxy} =\) major coefficient of permability with respect to water as a function of matric suction which varies with location in the \(s_1\)-direction, \(k_{wy}, k_{wyx} =\) major coefficient of permability with respect to water as a function of matric suction which varies with location in the \(s_2\)-direction, \(\partial h_{w}/\partial x =\) hydraulic head gradient in \(x\)-direction, \(\partial h_{w}/\partial y =\) hydraulic head gradient in \(y\)-direction, \(m_{w}^{2} =\) coefficient of water volume change and \(\partial h_{w}/\partial t =\) rate of hydraulic head gradient.

There were two types of seepage analysis involved in this numerical modeling namely steady-state seepage analysis and transient seepage analysis. These two analyses were used to study how infiltration varied over time and to investigate the relationship between infiltration-suction response and degree of saturation. In this numerical analysis, the input parameters involved are infiltration rate, groundwater table head, saturated hydraulic conductivity, suction range, air conductivity, saturated water content and sample material. **Table 6** shows the summary of input parameters of numerical modeling.

The conceptual model for numerical analysis is shown in **Figure 5**. Velocity vectors are a useful way of seeing not only where the flow is occurring, but how much flow there is relative to other regions of the domain. **Figure 6** shows the numerical model with velocity vector of infiltration into the soil.

In this study, soil parameters were obtained for the analysis of infiltration-suction response in unsaturated residual soil slope. A conceptual model was developed as well as the numerical simulation developed by finite element method (FEM). The evaluation was done to predict the relationship between soil infiltration-suction responses with respect to different degree of saturation.
| Input Parameters                          | Unit   |
|------------------------------------------|--------|
| Infiltration Rate                        | 1800mm/hr |
| Water Table Head                         | 0m     |
| Saturated Hydraulic Conductivity         |        |
| Depth of 0m-0.25m                        | 10.188mm/hr |
| Depth of 0.25m-0.5m                      | 12.744mm/hr |
| Depth of 0.5m-0.75m                      | 7.632mm/hr |
| Depth of 0.75m-1m                        | 2.556mm/hr |
| Suction Range                            | 0-11kPa |
| Air Conductivity                         |        |
| Depth of 0m-0.25m                        | 815.04mm/hr |
| Depth of 0.25m-0.5m                      | 1019.52mm/hr |
| Depth of 0.5m-0.75m                      | 610.56mm/hr |
| Depth of 0.75m-1m                        | 204.48mm/hr |
| Saturated Water Content                  |        |
| Depth at 0.25m                           | 0.15m³/m³ |
| Depth at 0.5m                            | 0.25m³/m³ |
| Depth at 0.75m                           | 0.11m³/m³ |
| Sample Material                          | SP, gravelly SAND for soil depth of 0m-1m |

**Figure 5.** Conceptual model for transient analysis (SEEP/W (Geostudio 2007)).

**Figure 6.** Numerical model with velocity vector of infiltration into the soil (SEEP/W (Geostudio 2007)).
5. Results and Discussion

5.1 Soil matric suction
Figure 7 shows the variations of elevation of soil correspond to matric suction from different depth. It can be observed that the highest matric suction value was 10kPa for depth of 0.5m. As the time increased, the matric suction for three different depths of residual soils decreased gradually. The residual soil was completely become saturated in 55 minute. As the soil completely saturated, the minimum matric suction achieved 0kPa. During dry seasons the matric suction in the soil increase and decrease during wet season [6]. The changes in matric suction were huge when near the ground surface. During a dry season, the evaporation rate was high and it results in a net loss of water from the soil. The opposite condition may occur during wet season.

Weathering process of residual soil leached the mineral in soil, which in turns caused the porous structure in soil. The value of matric suction was very high at this state. When rainfall infiltrate into the soil, it automatically replaces the pore air pressure with pore water pressure. At the end of this process, soil achieves saturated state and matric suction achieves minimum value. Therefore, it can be concluded that the decrease of the matric suction happens (as shown in Figure 7) because of the soil started to achieve its saturated state.

5.2 Volumetric water content
The volumetric water content of soil was increasing gradually in correspondence with time (as illustrated in Figure 8). From the results, it shows the highest value of volumetric water content after 55 minutes of test was 26.97% at soil depth of 0.5m. As the matric suction decreases, the permeability of the soil increases. It is also noticeable that as matric suction decreases, the volumetric water content of the soil increases.

Evaporation from soil brings the soil to a dry condition. When the soils started to dry (volumetric water content approaches 0%), the matric suction increased [10]. The volumetric water content was inversely proportional to the matric suction. At the beginning, unsaturated soil was majorly filled with air compared to water. When water infiltrate into the soil, these cause the air starts to be replaced by water. It is conclusive at this point that movement of water through the soil is faster when soil nearly achieved saturated state because there is more water filled spaces available for water flow.

5.3 Rate of infiltration
Figure 9 shows the rate of infiltration at various times obtained from the double-ring infiltrometer test. The result shows the infiltration rate decrease with time. At starting point the infiltration rate was 600mm/hr, after 55 minute it slowed down to 180mm/hr. Unsaturated soil was porous structure underneath. Water rapidly infiltrates into unsaturated soil at the beginning. When this porous structure starts to achieve saturated state, the porous structure was filled with water. Therefore, as conclusion, the more water replaces the air in the pores, the slower the water from the soil surface infiltrates and eventually reaches a steady rate.
Figure 7. Elevation of soil corresponds to matric suction from different depth.

Figure 4. Volumetric water content of soil correspond to time from different depth.

Figure 9. Rate of infiltration at various times obtained from the double-ring infiltrometer test.
5.4 Infiltration-suction responses over time

The respective responses at various times were illustrated in Figure 10 (a), (b) and (c). Figure 10 (a) shows the relationship of volumetric water content with infiltration rate. At the beginning, the infiltration rate are high because pore air pressure were high, therefore the water was very easy to seep into the soil. When the soil start to achieved saturated state, the infiltration rate starts to decrease, which means the water already fill the pore inside the soil and caused an increase of the volumetric water content in soil. Figure 10 (b) shows the matric suction and infiltration rate. As the soil becomes saturated state, the infiltration rate decreases and the air inside the soil were replaced by water so that the matric suction \( (u_a - u_w) \) nearly achieved 0kPa. Figure 10 (c) shows the relationship between volumetric water content and matric suction in soil. As the volumetric water content increases, soil suction decreases because the water replaces the pore air pressure. The graph of soil-water characteristic curve (volumetric water content versus soil suction) was shown in Figure 11. The plot shows the decreasing of soil suction as the volumetric water content increasing.
Figure 11. Soil-water characteristic curve for some Dutch soils [18].

It is important to have a preliminary qualitative understanding of the infiltration capacity and transient responses of matric suction and volumetric water content to an advancing wetting front in the instrumented soil sample. This could be achieved by performing a double-ring infiltration, tensiometer and TDR tests.

6. Conclusions

Factors affecting soil infiltration in residual soil slopes was obtained through the field and lab testing. The relationship between infiltration-suction response and degree of saturation verified and predicted by using finite element method (FEM) analysis. Besides, the contrasting soil behaviors identified to provide a more comprehensive understanding on the mechanism of rainfall induced slope failure. Influence of rainfall infiltration on changes in matric suction with time and the effects on unsaturated residual soil slope during rainfall have been also identified with the ground investigation data in this study.

In the future, numerical models can be used to integrate the rainfall scenarios into quantitative landslide hazard assessments. The development plans and mitigation measures can be designed for estimated impacts from hazard assessments based on collected data. Furthermore, hazard maps for the present situation and climate change scenarios of Penang can be generated providing decision support for solutions in dealing with the problem in this country.

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