Characterization the geotechnical properties of a Malaysian granitic residual soil grade V

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Abstract. Residual soils are produced from weathering of rocks and commonly found in tropical humid areas. The geotechnical properties of residual soils are a function of the parent rock, the degree of weathering, and climate which vary from region to region. A thorough quantification of the geotechnical characteristics of residual soils is required for a safe and economic structure design. This study attempts to summarize a series of important geotechnical properties of a Malaysian granitic residual soil grade V which determine the suitability and ability of the soil for construction including particles size distribution, specific gravity, plastic index, soil water characteristic curve, and shear strength. The findings were compared with geotechnical properties of other residual soils which were reported previously. The results showed weathering grade and the percentage of fine particles are the two important factors in controlling the geotechnical properties of residual soils.

1. Introduction

The entire Malaysian land with high average temperature (i.e. 27°C) and abundant rainfall in every month of the year experiences the wet type of tropical climate. The tropical climate is one of the main geological factors in the formation process of the residual soils. A thick mantle of residual soils covers more than 80% of Malaysia land [1]. These widespread soils are used conspicuously in the entire engineering construction work either to build upon or as construction materials. Therefore, a thorough quantification of the geotechnical characteristics of residual soils is required for a safe and economic structure design.

Unlike the more familiar transported sediment soil, the engineering properties and behavior of residual soils may vary widely from place to place depending upon the rock of origin and the local climate during their formation; and hence are more difficult to predict their engineering behavior mathematically [2]. A residual soil from an individual place needs to be characterized particularly for a proper assessment of its engineering properties. These soils are usually situated above the groundwater table and are often unsaturated. Being in the unsaturated zone makes their engineering behavior even more complicated.

Two major types of residual soils dominate Malaysia except for the coastal areas where covered by soft clay, which are granitic residual soil and sedimentary residual soils (sandstone) [3]. There is a wide distribution of granitic residual soil in Peninsular Malaysia (i.e. around 75% of the land area) since granites underlie many of the hills and mountains in this area. Granitic residual soil is defined as a
residual soil which remains of granite rock after its chemical and physical weathering [4]. The microstructure of granitic residual soils is controlled by particle size distribution and weathering grade. Typically, they are reddish in color and have a large void ratio. The percentage of fine particles (silt and clay) is little in their skeleton and padding and parceling of free oxides stick the coarse soil particles together [4]. The water content in Malaysian granitic residual soils is low and their liquid limit and plastic limit decrease with depth since clay content reduce with increasing depth. Their liquid limit, plastic limit, and plasticity index ranged between 25-110%, 18-50% and 1-74% respectively [5]. The percentages of sand, silt, clay and gravel vary based on the depth and location. According to the report by Ledgerwood [6], granitic residual soils range from plastic sandy silt soils at the surface to gravelly silty sand close to the unweathered rock. In some cases, the upper layers may be absent, leaving only the coarse grained gravelly sand. Salih [5] gathered the physical properties of granite residual soil reported by previous researchers in Malaysia (Table 1). Table 1 represents the physical properties of some Malaysian granitic residual soils which have been reported since 1994.

| Resource | Location | Clay (%) | Silt (%) | Sand (%) | Gravel (%) | LL (%) | PL (%) | PI (%) | Specific gravity, Gs | Weathering grade |
|----------|----------|----------|----------|----------|------------|--------|--------|--------|------------------|----------------|
Malaysian residual soils are prevalently in an unsaturated state except right away after rain due to the deep water table and extreme evaporative forces in hot condition [20]. Therefore, their strength needs to be investigated in both saturated and unsaturated conditions. Saturated shear strength of residual soils is produced from two major components of the resistance which are cohesion between particles ($c'$) and sliding friction between particles ($\phi'$). According to Salih [5], the saturated shear strength parameters of the granitic residual soils in Malaysia reported in the past publications were ranged between 7 – 77 kPa and 17 – 40° for $c'$ and $\phi'$ respectively. Rahardjo et al. [21] also investigated a value of $\phi'= 35°$ for granitic residual soil grade V. Gue and Tan [22] claimed that there is reduction in $\phi'$ with increased fines particles in Malaysian granitic residual soils. They also reported that $c'$ is generally zero or less than 10 kPa. However, for grade VI, the $c'$ value could be higher due to the increase in clay content. In addition, there is some evidence which reveals a rapid decline in shear strength to the point of zero where confining stress approaches zero [23-25]. In other words, shear strength behaves linearity at high confining stress levels and drops non-linearly when the confining stress approaches zero (apparent cohesion is generally zero at saturated condition).

In unsaturated conditions, the influence of shear strength related to suction is very important. The reduction of suction due to a development in pore water pressure has a serious influence on the stability of the structures. There are comprehensive studies on shear strength behavior of unsaturated residual soils over a large range of suction which proves the non-linearity of shear strength variation against suction [14, 19, 26, 27]. Various equations have been proposed to represent the shear strength of unsaturated soils [14, 19, 26, 27]. However, among them, Md. Noor and Anderson’s shear strength model (CSESSSM) [30] is a more comprehensive, constitutive shear strength model that represents the nonlinear shear strength behaviors of saturated and unsaturated soils. In this model, shear strength is produced from six major shear strength parameters. Minimum friction angle at failure, $\phi'_{min f}$, transition shear strength, $\tau_t$, and transition effective stress, $(\sigma - u_w)$t, represent the saturated shear strength and residual suction, $(u_a - u_w)_r$, maximum apparent cohesion, $c_s^{max}$, and the ultimate suction when the net stress is zero, $(u_a - u_w)_{\sigma=0}$ represent the unsaturated shear strength. The shear strength parameters of various soils applying CSESSSM are given in Table 2.

| Resources            | Soil type                    | Percentage of fine particles (%) | Saturated parameters | Unsaturated parameters |
|----------------------|------------------------------|---------------------------------|----------------------|------------------------|
|                      |                              | $\phi'_{min f}$ (degree)        | $(\sigma - u_w)_r$ (kPa) | $\tau_t$ (kPa) | $(u_a - u_w)_r$ (kPa) | $c_s^{max}$ (kPa) | $(u_a - u_w)_{\sigma=0}$ (kPa) |
| Saffari et al. [18]  | Granitic residual soil grade VI | 30                              | 25                     | 200                    | 120                    | 220                  | 110                        | 1800                     |
| Md. Noor [33]        | Washed gravel                | 0                               | 34                     | 200                    | 230                    | 15                   | 30                        | 50                       |
| Derahman [34]        | Coarse sand                  | 0                               | 30                     | 180                    | 168                    | 10                   | 32                        | 70                       |
| Mohamed Jais [17]    | Granitic residual soil grade VI | 29                              | 34                     | 200                    | 170                    | 110                  | 72                        | 800                      |
| Hadi [35]            | Granitic residual soil grade VI | 37.34                            | 20                     | 150                    | 85                     | 100                  | 120                       | 640                      |
| Md Noor & Derahman [36] | Granitic residual soil grade VI | 39.15                            | 16                     | 200                    | 120.24                 | -                   | -                         | -                       |
A soil-water characteristic curve (SWCC) that defined as the relationship between the water content of a soil and matric suction is another important engineering properties of unsaturated residual soils. SWCC curve is typically plotted as the matric suction or total suction versus gravimetric water content, \( w \), or volumetric water content, \( \theta \), or degree of saturation, \( S_r \), [37]. The matric suction at which a soil enters to its residual state is called residual suction. Beyond this point, the ratio of water content reduction to the suction will reduce and a large amount of suction is needed to transfer the water from the soil. The residual suction can be identified by the graphical method from SWCC curve [38]. Rahardjo et al. [21] reported that as the grain size and inter-particle pores of a soil increase, the ability of the soil to maintain water decreases. In another hand, in a granitic residual soli, as the soil becomes more weathered, more amount of clay minerals are produced and the ability of the soil to hold water under high matric suction increases or the residual suction of the soil increases.

It can be seen that the engineering characteristic and geotechnical properties of Malaysian granitic residual soil from different regions have been investigated in details by various researchers in the past [5, 11, 39, 40]. Nevertheless, these studies have not specifically considered the geotechnical engineering behaviour of granitic residual soil with respect to the degree of weathering and mostly concentrated on grade VI only. Most of the cut-slopes in Malaysia are exposed to the different grade of weathering and this influences the slope angles and stability and requires different soil stabilization measures. Thus, it is important to have knowledge of geotechnical behaviours of granitic residual soil in various weathering grades. This study attempts to summarize a series of important geotechnical properties of a Malaysian granitic residual soil grade V which determine the suitability and ability of the soil for construction including particles size distribution, specific gravity, plastic index, soil water characteristic curve, and shear strength. The findings will be compared with geotechnical properties of other residual soils which were reported previously.

2. Materials and Methods

The soil selected for this study was granitic residual soil obtained from Kuala Klawang, Malaysia as marked by red in Figure 1 (a) and (b). It can be observed from Figure 1 (b) that selected area is covered with granitic residual soils. Disturbed samples were collected using standard sampling equipment following BS 5930:2015 [41]. The topsoil was removed by a shovel until a depth of approximately 0.5 m and the disturbed samples were collected by means of a hand auger. The samples were put in plastic bags and stored in a large container for laboratory test purposes. Figure 2 shows a close view of the granitic residual soil at the obtained place. It can be seen that the color of the tested soil was reddish brown. Standard physical properties laboratory tests such as dry and wet sieving test, hydrometer test, Atterberg limits tests, and particle density test are used for the purpose of soil classification. In this research, physical properties tests were conducted in accordance with BS 1377:2016 [42] to ensure the accuracy and safety of the tests. A pressure plate was used to obtain SWCCs under zero net confining pressure, according to ASTM D6836-16 [43]. This test was applied for a series of matric suction from 10 to 800 kPa. In addition, the consolidated drained test, CD, was conducted in order to determine shear strength in saturated and unsaturated conditions using a conventional semi-automated triaxial apparatus and a modified double wall apparatus respectively. The suction of 0, 20, 50, 70, 90, and 120 kPa was applied on 6 specimens and each specimen was tested at 50, 100, 200, and 300 kPa confining pressures. The tests were conducted using multistage methods to reduce the number of specimens, sample preparation time and also equalization time.
3. Results and Discussion

3.1. Physical properties
In order to characterize the soil classification, soil particle size distribution curve was plotted based on the test results obtained from a combination of wet sieving, dry sieving and hydrometer test (Figure 3). The soil is classified as well graded very gravelly SAND in accordance with BS 5930:2015[41]. It contains of 45.32% gravel, 51.25% sand, 0.62% silt, and 2.81% clay. Besides that, the soil is classified as completely weathered grade V in compliance with weathering classification procedures specified in BS 5930:2015 [41]. A comparison between the percentage of particle size involved in the Kuala Klawang granitic residual soil grade V and the particle size distribution of granite residual soil reported by previous researchers in Malaysia (Table 1) it can be observed that the percentage of particle size
involved in the tested soil are within the range of percentage which is reported by Nithiaraj et al. [3] for granitic residual soil grade V from Perak. It can be seen that percentage of fine particles (silt and clay) are smaller and the percentage of sand and gravel are higher in the current study in comparison to most of the reported granitic residual soil. This is due to the variation of weathering grade which is reported by Komoo & Mogana [45] for residual soils in Peninsular Malaysia. The granitic residual soils reported in Table 1 mostly are characterized as grade VI of weathering except the one reported by Nithiaraj et al [3] which is grade V. According to Komoo & Mogana [45] in Malaysian grade VI residual soils, all the rock materials are converted to the soil and their material are generally silty or clayey. However, for the residual soils in grade V of weathering, the materials partially preserved and they are mostly sandy. Even though the soil is completely weathered, the texture of the rock is still preserved in the soil.

Figure 3. Soil particle size distribution curve.

The plasticity index (PI) of the tested soil was obtained from the Atterberg limits tests. The magnitude of the liquid limit, LL, plastic limit, PL, and plasticity index, PI were determined as 57.6%, 35.77%, and 21.83% respectively. The results are in agreement with the range of liquid limit, plastic limit and plasticity index for Malaysian granitic residual soils which were reported by Salih [5] (i.e. 25-110%, 18-50%, and 1-74% respectively). In addition, a comparison between Atterberg limits which were given at Table 1 for Malaysian granitic residual soil grade VI with the tested soil shows a reduction in Atterberg’s limits as weathering grade changes from grade VI to grade V. This is due to the reduction in clay content with increasing depth and decreasing in the weathering grade which is reported by Tan and Ong [46].

The specific gravity of Kuala Klawang granitic residual soil grade V was obtained as an average value of 2.65 Mg/m³. The value falls within the range of specific gravity value reported by Nithiaraj et al. [3] for granitic residual soil grade V from Perak (Table 1, i.e. 2.59-2.66 Mg/m³). On another hand, in Table 1 the value of specific gravity for granitic residual soils along Malaysia from the previous studies is given. The table shows a variation of reported value from 2.30 to 2.77 Mg/m³ based on the location. The obtained value of specific gravity for the soil tested in this research also falls within this range. However, the value is close to the uppermost boundary due to coarse particles involved in the soil. This finding supports the Tan and Ong [46] statement which reported the role of coarse particles in controlling the specific gravity of the granitic residual soils.

3.2. Soil water characteristic curve
The soil water characteristic curve of Kuala Klawang granitic residual soil grade V is given in Figure 4(a). The shape of the SWCC curve is in agreement with the typical SWCC curve for sandy soils which is provided by Fredlund and Xing [38] as shown in 4(b). The residual suction and residual water content were identified as 70 kPa and 15.4% respectively. The value of residual suction for the tested soil was compared with the value of residual suction presented in Table 2. It can be observed that value of residual suction for granitic residual soil grade V in this study (i.e. 70 kPa) is smaller than the value of residual suction reported for granitic residual soil grade VI from Hadi [35], Mohamed Jais [17] and Saffari et al. [18] (i.e. 100, 110, and 220 kPa respectively). In contrast, this value is significantly higher than the value of residual suction for gravel (i.e. 15 kPa) and sand (i.e. 10 kPa) reported by Md. Noor [33] and Derahman [34]. This can be explained by the variation of residual suction due to the particle size which is reported by Gan and Fredlund [26]. The value of residual suction decreases as the particle size increases. The presence of coarse particles especially gravel within the soil structure permits water to drain easily and thus the soil can desaturate relatively fast in comparison to fine soils. The percentage of fine particles present in granitic residual soil grade VI is more than grade V and relatively the residual suction is higher. In other words, there is no fine particle involved in washed gravel and sand and therefore the magnitude of residual suction present in these soils is smaller than granitic residual soil grade V.

Figure 4. (a) SWCC of Kuala Klawang granitic residual soil grade V (b) Typical SWCC provided by Fredlund and Xing [38] and the SWCC obtained for the tested soil

3.3. Shear strength
The saturated and unsaturated shear strength parameters of Kuala Klawang granitic residual soil grade V applying CSESSSM model are given in Table 3. The value of minimum friction angle, $\phi_{min}$, is comparable with results reported by Rahardjo et al. [21] for granitic residual soil grade V from Bukit Timah, Singapore (i.e. 35°). However, there is a nonlinear reduction in shear strength at stress levels less than 122 kPa and internal friction angle varies at the low stress range as illustrated in Figure 5. (i.e. effective stress of 50 and 100 kPa). The effective cohesion, $c^e$, was observed to be zero at the saturated condition. The evaluation agrees with the findings reported by De Mello [23], Indraratna et al. [24], and Maksimovic [25] on saturated soils. Figure 5 shows saturated shear strength envelopes for the tested soil and soils given in Table 2 using CSESSSM model. It can be observed that the value of the minimum friction angle at failure in the current study is similar to the reported value for gravel and granitic residual soil grade VI by Md. Noor [33] and Mohamed Jais [17] respectively. However, the value is not in agreement with the reported data by other researchers on granitic residual soil grade VI and sand. On the other hand, the magnitude of transition effective stress and transition net stress vary for each soil. It seems that there is no relationship between the saturated shear strength parameters. In fact, the variation of engineering properties of residual soils in different regions varies due to their parent rock, the degree of weathering, the amount of rainfall, topography, and temperature which is reported by Blight and Leong [2]. Thus, it is acceptable if the shear strength parameters of the tested soil are not in a good
agreement even with the shear strength parameters reported for Malaysian granitic residual soils grade VI.

Table 3. Shear strength parameters of Kuala Klawang granitic residual soil.

| Soil type                  | Saturated parameters | Unsaturated parameters |
|----------------------------|----------------------|------------------------|
|                            | $\phi_{\text{min f}}$ (degree) | $(\sigma - u_w)_{\text{r}}$ (kPa) | $\tau_{	ext{r}}$ (kPa) | $(u_o - u_w)_{\text{r}}$ (kPa) | $c_{\text{s max}}$ (kPa) | $(u_o - u_w)_{\text{n}}$ (kPa) |
| Granitic residual soil     | 34                   | 122                    | 105                    | 70                        | 31                        | 250                        |
| grade V                   |                      |                        |                       |                           |                           |                            |

Figure 5. The comparison between saturated shear strength envelopes of various soils using CSESSSM.

Figure 5 graphically compares the saturated shear strength envelopes of given soils in Table 2, against the effective stress using the saturated shear strength parameters. The figure indicates that the saturated shear strength of the given soils does not solely relate to the minimum friction angle at failure but it depends on the position of the envelopes in the $\tau - (\sigma - u_w)$ space. Also, it can be observed that the granitic residual soil reported by Md Noor and Derahman [36] and Hadi [35] have less shear strength compared to others. This can be due to the highest percentage of fine particles (i.e. 39.15 and 37.34% respectively) in compare to other soils. It is often assumed that the strength of soil decreases with increasing fines content [47]. Fine particles (i.e. clay and silt) has a tiny degree of friction angle due to the friction between particles [48]. In addition, the shape of soil grains affects the shear strength of the soils. Round grains are more likely to slip and roll than angular fragments. As the angularity increases, the ratio of rolling to sliding contacts decreases, which leads to greater shearing resistance [49]. In sandy soils, the friction angle can be affected by the graduation of sand. For example, medium-fine, well-rounded, and poorly graded sands have lower friction angles in comparison with coarser grained, well-grained, and/or angular sands [50].
The unsaturated shear strength parameters of the current study were compared with previous research using CSESSSM as given in Tables 2 and 3. From these parameters, the variation of apparent shear strength due to suction was plotted in Figure 6. The figure shows that the value of residual suction, \((u_a - u_w)_r\), maximum apparent shear strength, \(c_s^{\max}\), and ultimate suction, \((u_a - u_w)_u\), for granitic residual soils grade VI with a high percentage of fine particles are greater than other soils. In other words, coarse sand and gravel have the lowest value of unsaturated shear strength parameters. Therefore, it can be concluded that fine particles have a strong influence on unsaturated shear strength parameters of soils. In fact, the shear strength of an unsaturated soil which contains fine particles is more sensitive to the variation of suction than a coarse soil. As a result, the wetting collapse which is due to the reduction in suction can be more problematic in this kind of soils rather than sand and gravel. The finding assents to the statement reported by Huat et al. [51].

![Figure 6. The comparison between the variation of apparent shear strength due to suction of various soils using CSESSSM.](image)

4. Conclusions
A series of important geotechnical properties of a granitic residual soil grade V from Kuala Klawang, Malaysia were investigated. The findings were compared with geotechnical properties of other residual soils which were reported previously. The study showed that percentage of fine particles (silt and clay) for granitic residual soil grade V were smaller and the percentage of sand and gravel were higher in comparison to most of the reported granitic residual soils in Malaysia. The Atterberg limits and specific gravity of the soil were within the range of reported data for Malaysian granitic residual soils. A comparison of these values with the reported value from previous researchers proves the ability of fine particles in controlling the Atterberg limits and specific gravity. Lowest weathering grade produces less percentage of fine particles, reduces the Atterberg limits and increases the specific gravity. The conducted study also confirms that the percentage of fine particles has a large influence in determining residual suction. The residual suction of the tested soil was greater than gravel and sand and smaller than grade VI granitic residual soils. In addition, the saturated and unsaturated shear strength parameters of the tested soil applying CSESSSM model was determined. The value of minimum friction angle was comparable with previous results reported for granitic residual soil grade V. However, the effective cohesion, \(c'\), was observed to be zero at the saturated condition. The integration of shear strength parameters for various soil obtained that fine particles have a strong influence on unsaturated shear
strength parameters of soils. In fact, the shear strength of an unsaturated soil which contains fine particles is more sensitive to the variation of suction than a coarse soil. Thus, it can be concluded that weathering grade and the percentage of fine particles are the two important factors in controlling the geotechnical properties of granitic residual soils.

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