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Remolded Saturated Residual Sedimentary Soils in Jengka, Malaysia: Analyzing Physical, Mechanical, and Critical State Properties

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ABSTRACT

The widespread occurrence of residual soils in Malaysia presents a significant challenge to the construction industry due to their highly unpredictable and variable nature. Residual soils, which include types such as granite residual soil and sedimentary residual soil, are formed through the weathering of parent rock, and they are commonly found across various regions in Malaysia. This study specifically focused on saturated sedimentary residual soil from Jengka area in Pahang, which has been less explored compared to other types of residual soils. Given the lack of prior research on this soil type, it was chosen for detailed investigation to better understand its physical, mechanical and critical properties. A total of 12 remolded soil samples, each with dimensions 2 in 1 which is 100 mm in height and 50 mm in diameter, were tested using consolidated drained triaxial testing methods to determine key parameters. The results classified the saturated sedimentary residual soil as silty sand with medium plasticity. The mechanical strength values recorded for the soil include an average effective cohesion (c') of 27.7 kPa and an effective friction angle (ϕ') of 30°. In addition to these mechanical properties, four average critical soil parameters were documented which are M 1.4637, λ 0.102, κ 0.018, and Γ 2.019. These values are essential for accurately predicting the behavior of sedimentary residual soils, providing engineers with the data needed for safer geotechnical structure design, including retaining walls and building foundations.

Keywords: Residual sedimentary soil; physical; mechanical; critical state; remolded

INTRODUCTION

Geotechnical engineering is a highly important field within the construction sector as the even distribution of load on the soil plays a major role in ensuring the stability of the structures built. To achieve an even load distribution, various aspects need to be considered, such as the amount of load from the structure and the type of soil receiving that load. Soil is generally classified into two types: residual soil and transported soil. The formation processes of these soils go through various stages, and their classification is based on the formation process.

Residual soil and transported soil have different formation histories, which result in different soil properties. For example, residual soil, as reported by many researchers (Taha et al. 1997; Ali, 1990; Huat & Singh, 2004; Huat et al. 2006; Raharjo et al. 2012; Salih & Kassim, 2012; Wibawa et al. 2018; and Zhang et al. 2020), exhibits much uncertainty due to varying degrees of weathering at different soil depths and varying weathering processes. Tropical residual soil, unlike other transported soils, may have engineering properties and behavior that differ and are more difficult to predict and model based on mathematical calculations (Raharjo et al. 2012).

In Malaysia, studies by Nithiaraj (1996) and Ting et al. (1972) have shown that residual soil consists of a mixture of sand, silt, and clay in varying ratios depending on the soil's geology. Taha et al. (1997) reported that residual soil covers more than three-quarters of the area in Peninsular Malaysia. This aligns with the statement by Amin et al. (1997) that granite and sedimentary residual soils dominate most of the land in Malaysia, except coastal areas, which are dominated by soft clay.

Residual sedimentary soils are formed from the weathering of parent rock in place, leading to a mix of particle sizes and mineral compositions. Such variability is expected in natural soils, resulting in slight differences in strength parameters across different samples. Figure 1 shown the geological background of soil in Malaysia and the location of soil sample for this study.

The critical state concept provides an integrated concept related to soil behavior, combining specific stress and volume values of soil that are interrelated with each other. This concept was first introduced in 1958 by Roscoe, Schofield, and Wroth in writings related to soil deformation. In 1963, Roscoe et al. conducted triaxial tests on normally consolidated and slightly over consolidated soils. The study was continued by Schofield and Wroth (1968), who summarized all the experimental results carried out by Roscoe et al. (1963) to be applied to both sand and clay soils.

From the previous studies, it has been observed that researchers have focused more on granite residual soils, with comparatively fewer studies on sedimentary residual soils in Malaysia, despite their extensive use in the construction sector. This may be attributed to the greater distribution of granite residual soils compared to sedimentary residual soils. Therefore, to address this gap, the aim of this research is to determine the physical, mechanical behavior and critical state parameters of saturated sedimentary residual soil.

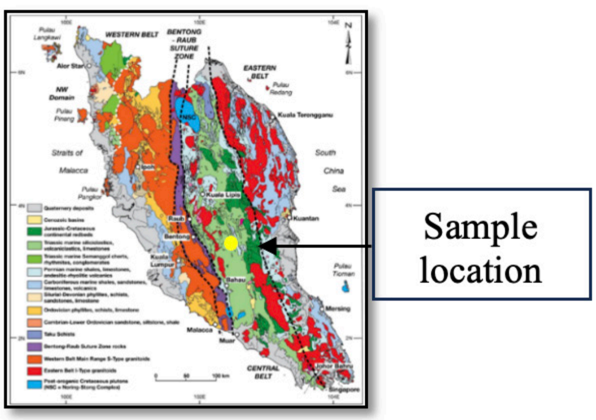


FIGURE 1. Geological background of Malaysia (Hutchison and Tan 2009)

METHODOLOGY

LOCATION

The location for soil sampling of this study is at the foothill area of the UiTM Pahang Jengka Campus forest reserve near the water tank of Block Infra Science Tech (IST) with coordinates 3°45'33.7"N 102°34'00.0"E as shown in Figure 2. Based on the background of soil types in Peninsular Malaysia (Figure 1) by Hutchison and Tan (2009), the soil sampling location is residual sedimentary soil (limestone). All soil samples collected were disturbed samples, taken using a hand auger and traditional methods. The soil samples were taken at a depth of 1.0 – 1.5 m, with the top 0.5 m layer being removed before the soil samples were placed into airtight containers and transport to nearby Makmal Kekuatan Tanah at block IST to minimize the soil disturbance.

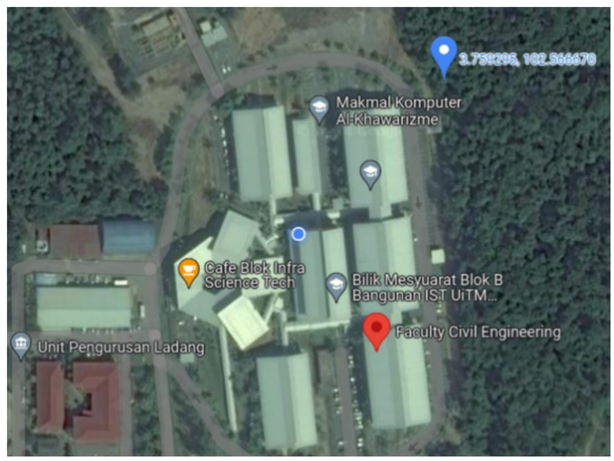


FIGURE 2. Location of soil sampling at UiTM Pahang, Jengka Campus

EXPERIMENT DESIGN AND PROCEDURE

To determine the physical and mechanical properties, as well as the critical state parameters of saturated residual sedimentary soil, the collected soil samples will undergo standard physical soil tests, namely moisture content, particle size distribution, Atterberg limits, specific gravity, and compaction. The soil classification is then carried out by comparing the obtained data with soil classification references, BS 5930:2015 and ASTM D2487-17.

The soil samples will then go through a compaction test before the consolidated drained (CD) test is conducted. Carefully trim the sample to the required dimensions (50 mm diameter and 100 mm height) and make the smooth ends ensure even contact with the loading plates during the test. While on this stage, the sample was handled in room temperature to maintain its natural moisture content. By following these steps, disturbance to the soil sample can be minimized, ensuring that the triaxial test results accurately reflect the in-situ properties of the soil.

Utilizing two standard, British Standard (1990), Methods of Test for Soils for Civil Engineering Purposes (BS 137, Part 1-9-1990), and Head, K.H. (2014), Manual of Soil Laboratory Testing, Volume 1: Soil Classification and Compaction and Volume 3: Effective Stress Test, the soil tests can be performed. The triaxial tests are conducted using GDS (Geotechnical Digital System) triaxial apparatus connected to a computer for data recording. In this study, three sets of remolded CD tests (with four samples for each set) of 100 mm height and 50 mm diameter are conducted, with each set subjected to effective confining pressures of 50, 100, 200, and 400 kPa, and a strain rate of 0.1 mm/min.

The chosen pressures (50, 100, 200, and 400 kPa) cover a broad range of confining conditions that soils may experience in the field. Lower pressures (50 kPa) might represent shallow depths, while higher pressures (400 kPa) could simulate deeper geological conditions. By testing multiple confining pressures, it is possible to observe the soil's behavior under different stress paths, helping to define the critical state line and the yield surface in stress space, which are essential for parameters in models like the Modified Cam Clay.

For remolded samples, the selected strain rate helps in capturing the true drained response of the soil, which is essential in understanding the soil's long-term behavior underload. A strain rate of 0.1 mm/min is generally slow enough to avoid significant rate effects but fast enough to complete the test in a reasonable timeframe. This rate ensures that pore pressure dissipation occurs, crucial in CD tests, where the aim is to observe soil behavior without excess pore pressure influencing the results.

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES OF SOIL

Table 1 shows the values of physical properties of residual sedimentary soil, classified as silty sand with brownish in color for 1.0 – 1.5 m depth. The soil in this research was classified as silty SAND (SM) with medium plasticity. Thiruchelvam et al. (2024) reported for sedimentary residual soil in UNITEN Bangi Campus, the soil was classified as clayey silt even though it is sedimentary soil. Kang and Juntao (2021) classified the granite residual soil in Shenzhen, China, as clay with high plasticity. Notably, Shenzhen area is characterized by a warm and humid climate same as Malaysia. This demonstrates that soil classification can vary by location, even for residual soils in similar climatic or geological conditions.

These soil properties are crucial in designing as example foundations and slopes in Malaysia, where tropical weather and rainfall patterns play a significant role in influencing soil behavior and stability. By referring to the soil classification, silty sand with medium plasticity suggests a mixture of sand and silt with low clay content. This classification indicates moderate permeability and drainage capacity, which can affect both foundational stability and slope behavior. For settlement, this type of soil can exhibit moderate consolidation and settlement under loads, while for slope, the silty nature of the soil could lead to reduced shear strength and increased risk of slope failure under intense rainfall, a common issue in Malaysia.

As a prevention approach, drainage control can adhere by designing efficient drainage systems to manage surface and groundwater, reducing the risk of pore pressure build-up. Slope Reinforcement and slope stabilization techniques such as retaining walls, geotextiles, or vegetation to mitigate erosion and enhance stability, while regular monitoring must be Implement regular to monitor of slopes, especially during and after heavy rainfall, to detect early signs of instability.

TABLE 1. Physical properties of soil

Physical characteristics	Value
Depth (m)	1.0 – 1.5
Color	Brownish
Moisture content, w (%)	18.82
Maximum dry density, MDD (kg/m^3)	1776
Optimum moisture content, OMC (%)	15.8
Specific gravity, (Gs)	2.62
Liquid limit, LL (%)	39.85
Plastic limit, PL (%)	25.08

continue ...

... cont.

Plasticity index, PI (%)	14.77
Gravel (%)	13.42
Sand (%)	41.93
Silt (%)	42.17
Clay (%)	2.48
Classification	Silty SAND (SM) (silty sand soil with medium plasticity)

MECHANICAL PROPERTIES OF SOIL

Figure 3 (a), (b) and (c) shows the failure envelope. The soil strength parameters cohesion, c' and internal friction angle, ϕ' recorded for the three sets of samples are 26 kPa, 28 kPa and 29 kPa and 29°, 31° and 30° respectively. On average, the c' and ϕ' values recorded are 27.7 kPa and 30°. The average c' indicates a consistent level of particle bonding and a modest degree of cohesion, typical of silt-dominated soils with minor clay content. While for ϕ' value, it indicates a relatively high friction angle, which suggests good shear resistance due to interparticle friction. This range is typical for soils with a balanced composition of sand and silt, where particle interlocking contributes significantly to shear strength. As mentioned by Mamat et al. (2023), all parameters of soil strength are indispensable in constructing various structures such as roads and building foundations.

The result of a study of residual sedimentary soil obtained in Sepang, Selangor by Huat et al. (2005), using the CD test, recorded the range of soil strength parameters c' and ϕ' as 0 - 10 kPa and 26 - 33° respectively. While in this study found that the c' value recorded for the CD test was higher compared to the results of Huat et al. (2005), however the ϕ' values are in the same range. Cohesion contributes to the soil's ability to support loads. A higher c' value increases the soil's bearing capacity, making it more suitable for supporting the weight of structures and roads. Higher c' value also helps in resisting shear stress, which is crucial for preventing failure in soil underload. While the ϕ' contributes to the overall shear strength of the soil. Soils with a higher ϕ' can better resist shear forces, reducing the risk of foundation failure, resistance to slope from sliding and foundation will not experience excessive settlement or tilting.

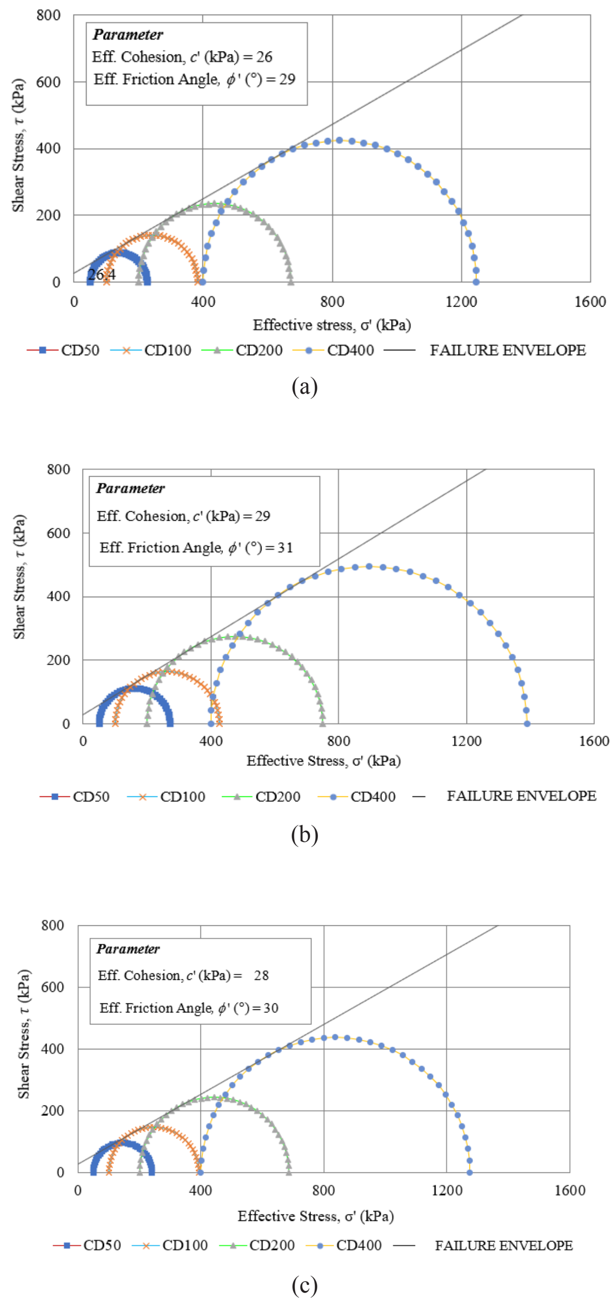


FIGURE 3. (a), (b), (c) Mohr-Coulomb failure envelope for sample A, B, C

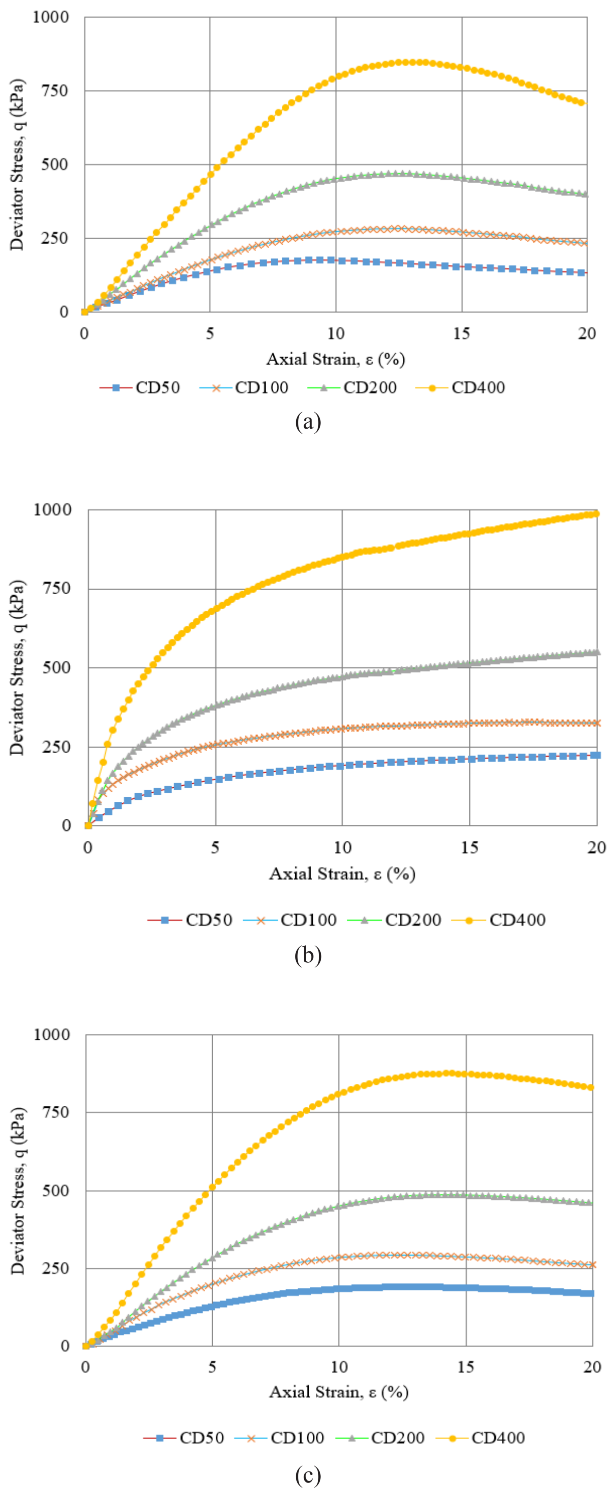


FIGURE 4. (a), (b), (c) Deviator stress – axial strain for sample A, B, C

Figure 4 (a), (b) and (c) shows the deviator stress versus axial strain. All the samples tested showed brittle failure. When brittle failure occurs, the sample experiences an increase in shear stress until it reaches a maximum point before decreasing and reaching a uniform shear stress value. The higher the effective confining pressure applied to the sample, the higher the recorded maximum shear stress and axial strain. Samples with effective confining pressures of 50 kPa and 100 kPa exhibited less pronounced brittle failure patterns compared to samples with an effective confining pressure of 400 kPa. The maximum shear stress values are important in the Critical State Model (CSM) because these values will be used by engineers in designing geotechnical structures. In this study, all samples were tested until reaching 20% axial strain. As stated by Marto et al. (2016), the critical state of the soil is defined when pore water pressure becomes constant or when the soil is sheared to 20% of the axial strain, whichever occurs first.

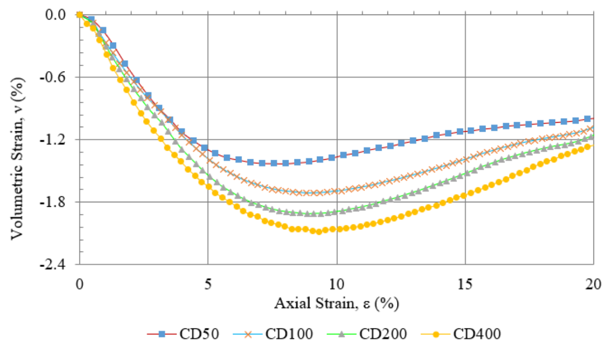
While Figure 5 (a), (b) and (c) below shows the volumetric strain curve, ν (%), against axial strain, ε (%). All the samples exhibited similar volumetric strain patterns, with no sample recording a uniform volumetric strain reading. For example, sample A CD400, the negative volumetric strain increased rapidly until it reached -2.05% at 9% axial strain. After that, the curve reversed with a decrease in negative volumetric strain, indicating an increase in positive volumetric strain, although it did not return to its original state. This indicates that all samples underwent a contraction process before the expansion process occurred.

Overall, the graph shows that the soil samples experienced significant contraction at the early stages, followed by expansion after reaching the minimum volumetric strain point. This behavior is characteristic of soils undergoing internal structural adjustment when subjected to stress, where contraction precedes expansion.

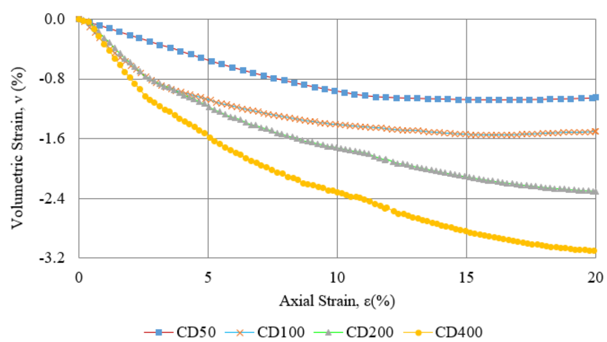
CRITICAL STATE PARAMETERS OF SOIL

Figure 6 (a), (b), (c) shows the critical parameter that represents the critical slope value, M of the q-p' graph. The M value obtained for each sample is in the range of 1.242 - 1.7919 with R^2 coefficient value of 1. On average, the M value for set A is 1.4104, set B 1.5376, set C 1.443 and the average value of M for all samples is 1.4637. Nagendra et al. al (2013) found that for the saturated residual sedimentary soil in Vinayaka Nagar and Gayathri Nagar, the value of critical slope M obtained was 3.1 for an effective confining stress of 50 kPa and 1.4 for an effective confining stress of 100 kPa. This indicates that the higher the effective confining stress is given, the smaller the M value recorded. This pattern is similar with the results obtained in this study.

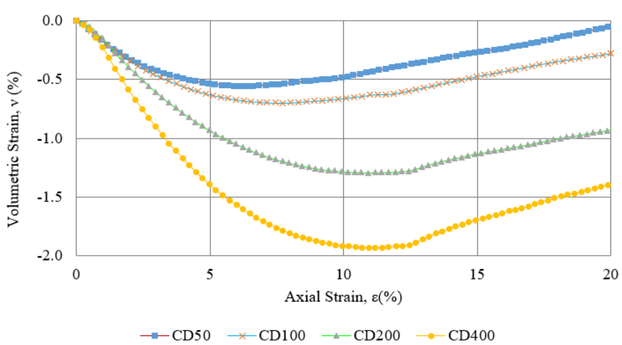
M is directly related to the shear strength of the soil at critical state. It helps in predicting the maximum shear strength the soil can sustain before it reaches a plastic flow condition. In foundation design, knowing M value will assist in determining the failure criteria for soils under different stress paths, crucial for safe and efficient foundation design.



(a)

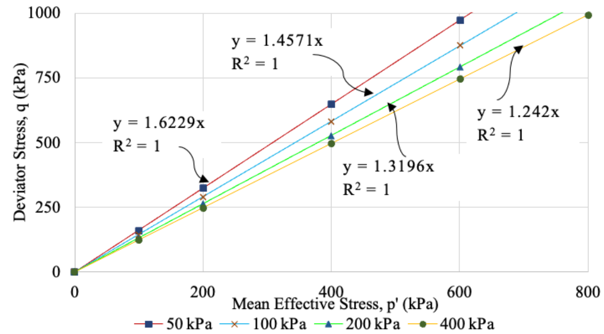


(b)

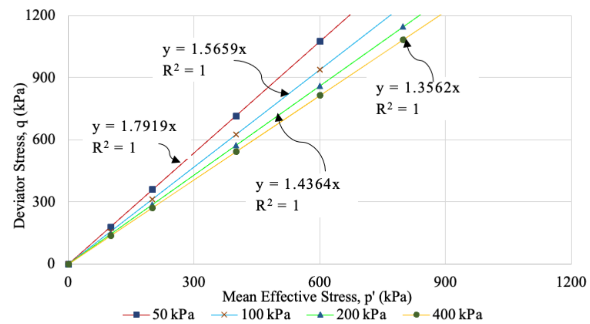


(c)

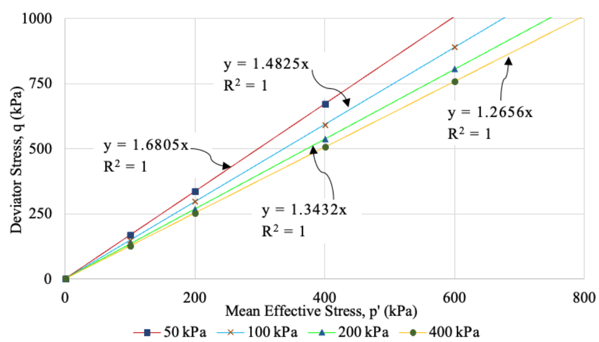
FIGURE 5. (a), (b), (c) Volumetric strain – axial strain for sample A, B, C



(a)



(b)



(c)

FIGURE 6. (a), (b), (c) Critical slope value, M

The next critical state parameters are the values of λ, κ, and Γ, which can be obtained from the graph of void ratio, e, against effective mean stress, p'. Figure 7 shows the e-p' graph for each sample. The value of λ represents the gradient of the graph, the value of κ is the gradient of the graph during unloading, while the Γ is the value of at x axis when the value of p' equal to 1 kPa. Figure 6 shows the graph of an e- p' for all the set samples.

The range of λ values obtained is between 0.087 – 0.116, with an average value of 0.103 for set A, 0.102 for set B, 0.102 for set C, and the overall average λ value for the CD test being 0.102. This parameter indicates the soil's compressibility under loading. A lower value suggests a less compressible soil, which is desirable for minimizing settlement in structures. It's also crucial for predicting and mitigating long-term settlements in foundations, embankments, and other earth structures. Meanwhile, the range of κ values obtained is 0.015 – 0.021, with an average value of 0.018 for set A, 0.0175 for set B, 0.018 for set C, and the overall average κ value for the CD test is 0.018. κ represents the soil's capacity to recover its shape upon unloading. This is important in designing structures that undergo cyclic loading, such as bridges and retaining walls. A smaller value of *κ* indicate that the soil has low swelling potential, which is beneficial for structures where volume stability is critical.

The next critical parameter, Γ, is between 2.008 – 2.013. The average value of Γ for set A is 2.011, for set B is 2.009, for set C is 2.013, and the overall average Γ value obtained for the CD test is 2.019. Value of Γ provides information about the initial structure or density of the soil. A high Γ value indicates a looser initial soil structure and it is used in defining the critical state line, aiding in the prediction of soil behavior under varying stress paths, which is essential for complex geotechnical analyses such as in deep excavations or tunneling. This shows that the higher the effective confining stress applied to the soil sample, the larger the values of λ, κ, and Γ recorded. Table 2 below summarizes the critical state parameters of the saturated residual sediment soil in this study.

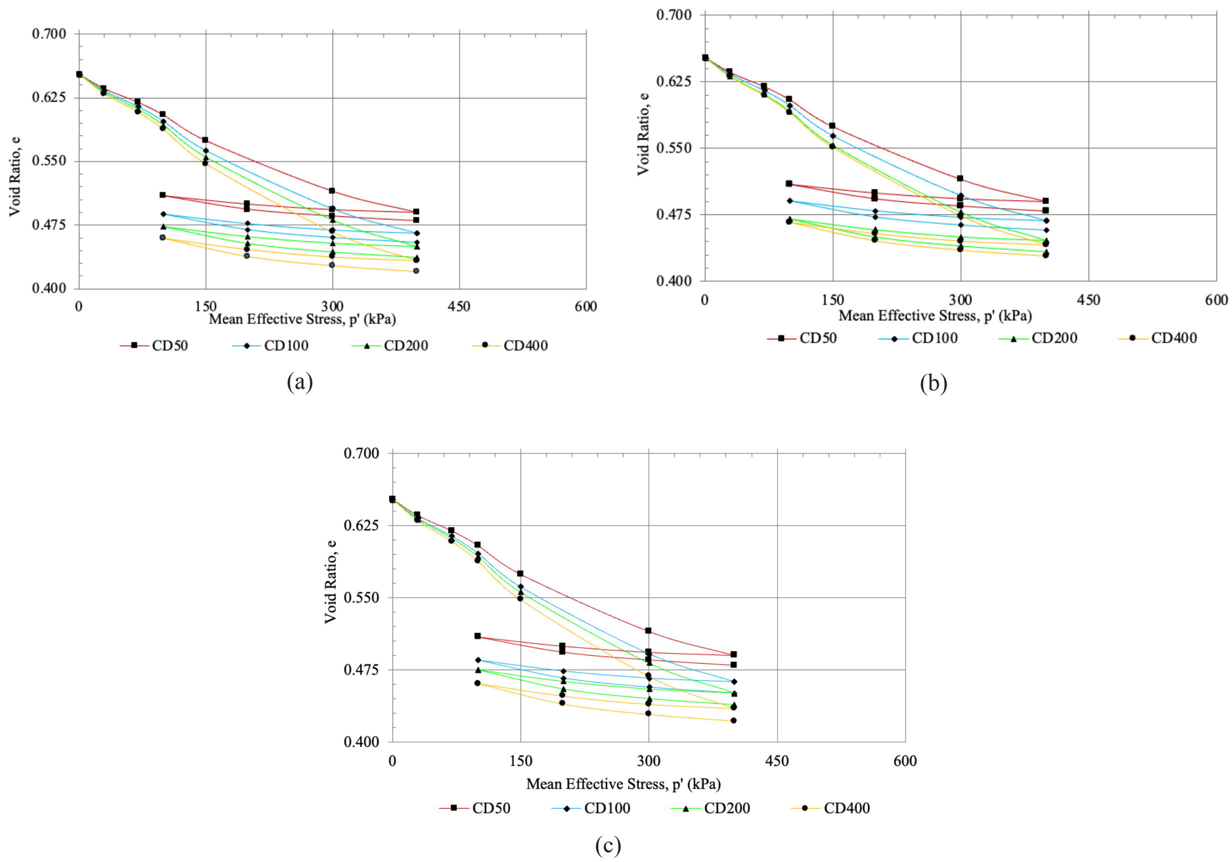


FIGURE 7. (a), (b), (c) Graph *e-ln p*

Kayadelen et al. (2007) reported that the critical state parameters for residual clay soil were M 0.879, λ 0.074, and Γ 2.32 based on their prior research, while Toll and Ong (2003) discovered that the values for sandy clay in Singapore's Jurong area were M 1.23, λ 0.08, and Γ 2.0. Additionally, M was 1.11, λ was 0.039, Γ was 2.010, and κ was 0.011 in Mofiz et al. (2005) research on residual granite soil at UKM Bangi, Malaysia. On the other hand, M 1.2879, λ 0.04, κ 0.014, and Γ 1.02 were the somewhat different critical state values reported by Taha and Asmirza (2001) for the remaining granite soil in UKM Bangi.

Consequently, it can be state that the critical state parameter values that researchers have previously reported fall between M 0.879 – 1.2879, λ 0.039 – 0.08, κ 0.014, and Γ 1.02 – 2.32. The values of λ an κ in this research are higher compared to the previous range, indicating that the sedimentary residual soil in the Jengka area has a greater tendency for settlement and swelling. Conversely, the Γ value falls within the range of previous studies, suggesting that the initial soil structure is moderate.

TABLE 2. Crirtical parameters of saturated sedimentary residual soil

Triaxial Test	Sample No.	Sample Code	Critical Parameters							
			M	$M_{average}$	λ	$\lambda_{average}$	κ	$\kappa_{average}$	Γ	$\Gamma_{average}$
CD	A	CD50	1.6229	1.4637	0.087	0.102	0.015	0.018	2.008	2.019
		CD100	1.4571		0.100		0.018		2.010	
		CD200	1.3196		0.109		0.019		2.012	
		CD400	1.2420		0.116		0.021		2.103	
	B	CD50	1.7919		0.087		0.015		2.009	
		CD100	1.5659		0.100		0.017		2.011	
		CD200	1.4364		0.109		0.019		2.013	
		CD400	1.3562		0.112		0.019		2.015	
	C	CD50	1.6805		0.087		0.015		2.010	
		CD100	1.4825		0.101		0.018		2.012	
		CD200	1.3432		0.106		0.019		2.013	
		CD400	1.2656		0.113		0.020		2.016	

CONCLUSION

This study contributes by providing empirical data on the behavior of Jengka's sedimentary soils under triaxial testing conditions. It enhances the understanding of local soils in geotechnical modeling, which might previously rely on more generalized or less specific soil data. In Malaysia, while research on the critical state parameters of sedimentary residual soils is still limited, their use in construction is widespread. Thus, findings based on this study might influence local building codes or soil management practices, promoting the use of region-specific data in planning and development. Critical soil parameters, as used in geotechnical engineering, are variables that aid in understanding and forecasting how soil will behave under stress or pressure. The findings could inform foundation design, slope stability analysis, and earthwork operations in the Jengka area, ensuring safer and more cost-effective engineering solutions. Engineers can utilize the physical, mechanical, and critical values identified in this study as a reference for their designs. For further research, the findings can be integrated with advanced geotechnical software, using models calibrated to local conditions. This approach aims to enhance design efficiency and improve research outcomes.

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DECLARATION OF COMPETING INTEREST

None.

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