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# Characterization and Shear Strength Evaluation of Sensitive Volcanic Residual Soils in West Java

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**ABSTRACT** Volcanic residual soils in tropical regions exhibit unique engineering behavior that differs significantly from sedimentary soils. These soils often contain amorphous clay minerals such as allophane and halloysite, which contribute to their sensitivity and unusual strength characteristics. Field observations in West Java revealed near-vertical, free-standing cuts up to 12 meters high, indicating apparent cohesion supported by natural cementation and unsaturated conditions. A geotechnical investigation was carried out using standard penetration tests (SPT), cone penetration tests with pore pressure measurement (CPTu), and laboratory tests including Atterberg limits, index properties, and unconsolidated-undrained triaxial tests. Results show that Su values obtained from CPTu are more consistent with laboratory triaxial data, while SPT correlations tend to underestimate strength due to sample disturbance. Furthermore, particle size analyses confirm the gap-graded nature of volcanic residual soils, reflecting differential weathering processes. This study aims to establish representative undrained shear strength parameters of sensitive volcanic residual soils in West Java by integrating field and laboratory investigations. The findings highlight the importance of careful sample handling, the use of less-disturbing in-situ tests, and the selection of appropriate testing methods to obtain reliable soil parameters for engineering design. These findings provide practical implications for the characterization and modeling of sensitive volcanic residual soils in engineering applications.

**KEYWORDS** residual soil, volcanic soil, undrained shear strength, soil investigation, sample disturbance

## 1. INTRODUCTION

From a geological perspective, tropical volcanic regions commonly produce residual soils derived from the weathering of andesite, basalt, and tuff. Volcanic residual soils exhibit distinctive characteristics that contrast with sedimentary soils. These soils often possess very high natural water content with a liquidity index (LI) greater than one, which classifies them as sensitive soils prone to significant loss of shear strength when disturbed. Conversely, field observations within the study area reveal that the soil can remain stable in an unsupported condition, forming near-vertical slopes up to 10-12 meters high. This paradox between high sensitivity and apparent stability highlights the complexity of their physical behaviour.

In tropical volcanic environments, prolonged weathering under humid climatic conditions results in fine-grained soils with variable structure, particle size distribution, and cementation effects. These factors contribute to the apparent cohesion and strength that allow free-standing slopes to develop in the field. However, their engineering characterization is often challenging due to the combined effects of structure, suction, and partial saturation. Conventional penetration tests such as the standard penetration test (SPT) tend to produce overly conservative results because of sample disturbance and the difficulty of representing the in-situ condition of these soils. In contrast, the cone penetration test with pore pressure measurement (CPTu) provides a more continuous and reliable profiling, making it more suitable for evaluating sensitive volcanic residual soils.

Despite these observations, limited studies have been conducted to systematically compare the results of different testing methods and their implications for determining representative shear strength parameters of volcanic residual soils. This knowledge gap has led to uncertainties in design parameters, especially when these soils are encountered in slope stability or excavation analyses.

Therefore, this study aims to characterize the engineering behavior of sensitive volcanic residual soils in West Java and to establish representative undrained shear strength parameters through the integration of field (SPT and CPTu) and laboratory (triaxial and index property) investigations. The research also evaluates the reliability of conventional empirical correlations in comparison with direct measurements, providing a practical framework for interpreting and modeling volcanic residual soils in tropical environments.

## 2. METHODOLOGY

The geotechnical investigation at the site consisted of a combination of field and laboratory testing, designed to characterize the physical and mechanical behaviour of sensitive volcanic residual soils and to establish representative shear strength parameters.

### 2.1. Field Investigation

A total of four boreholes were drilled to maximum depth of 35 meters, with standard penetration test (SPT) performed at 1.5-meter intervals in accordance with ASTM D1586. These tests provided an indication of the soil strength for the laboratory testing. In addition, four cone penetration tests with pore pressure measurement (CPTu) were conducted following the ASTM D5778 to provide continuous stratigraphic profiles, soil behaviour type classification, and estimates of in-situ strength and stiffness parameters. The CPTu soundings were positioned adjacent to the boreholes to ensure that both datasets represented the same subsurface conditions.

### 2.2. Laboratory Testing

Representative soils samples from the boreholes were tested to determine index and strength properties. The testing program included:

- Atterberg limits (ASTM D4318)
- Natural water content and specific gravity (ASTM D2216 and D854)
- Unit weight and void ratio (ASTM D7263)
- Unconsolidated-undrained (UU) triaxial tests (ASTM D2850) for shear strength evaluation

Oven-drying of samples was carried out at $105 \pm 5^{o}$C as recommended by ASTM D2216.

### 2.3. Data Analysis

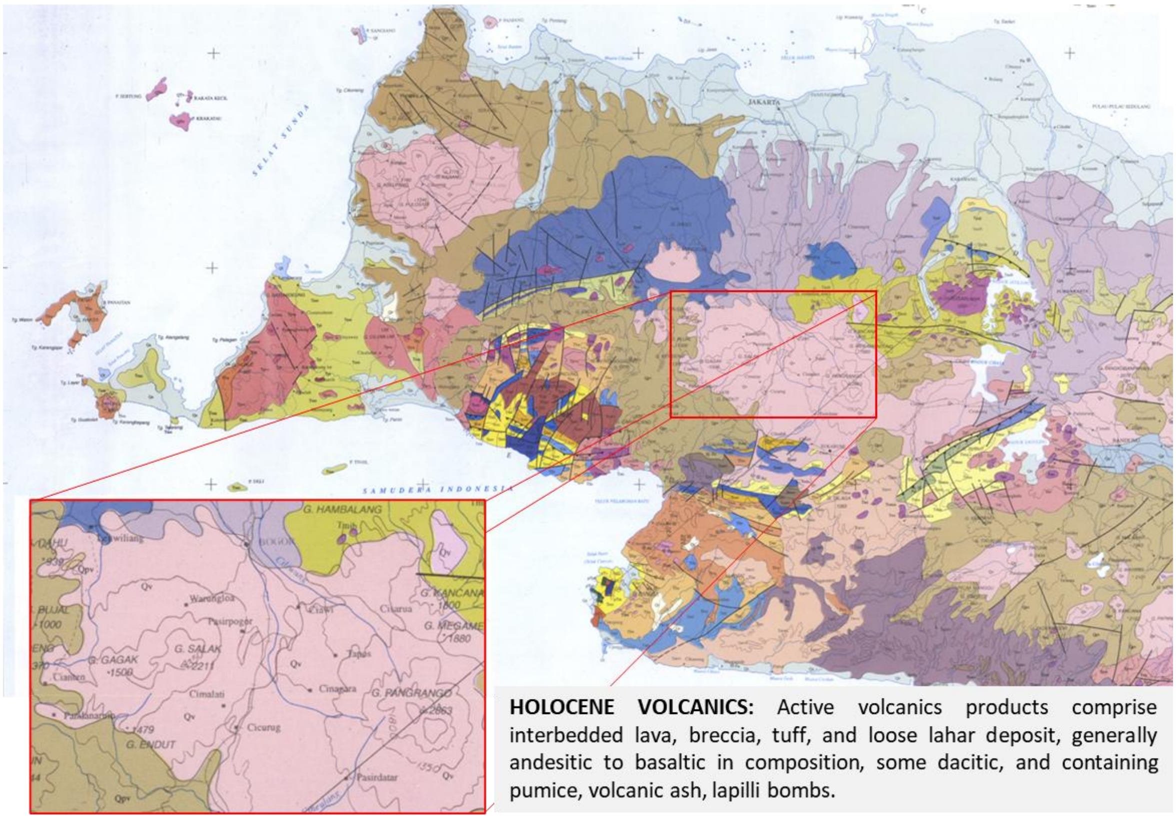
The consistency and undrained shear strength of the soils were interpreted using established empirical correlations. For SPT results, the relationship between N-value and Su followed the correlations proposed by Szechy and Varga (1978) and Terzaghi and Peck (1967). For CPTu data, the interpretation adopted the approaches of Meyerhof (1965) and Terzaghi and Peck (1984), which relate Su to cone resistance through an empirical cone factor (Nkt).

Field and laboratory data were analyzed to interpret soil stratigraphy, index properties, and undrained shear strength (Su). The Su values from field investigations were obtained through correlations with N-SPT and qc values. The Su from N-SPT was estimated using empirical relationships of Su = 5N, 7N, and 10N to illustrate the closeness with laboratory and CPTu results. A *cone factor* (Nkt) of 15 was applied for estimating Su from CPTu. The *triaxial UU* test results were normalized against the confining pressure of the samples. These results were compared with laboratory triaxial test data to evaluate consistency and reliability or providing Su values representative of the in-situ conditions at the test depth. The back-calculated Nkt for this residual volcanic soil ranged from 12 to 15, falling within the commonly accepted range of 12–20 reported in the literature. This result is further supported by Wesley (2009), who suggested a reasonable average value of Nkt = 15 for similar soil conditions.

## 3. VOLCANIC RESIDUAL SOIL CHARACTERIZATION

The study area is located in West Java, which is geologically dominated by Quaternary volcanic products, particularly young volcanics of Holocene age. This region is covered by the Holocene Volcanics formation, consisting of interbedded lava, breccia, tuff, and loose lahar deposits. The lithology is generally andesitic to basaltic in composition, with some dacitic portions, and often contains pumice, volcanic ash, and lapilli (Ratman & Gafoer, 1998).

In areas with elevations exceeding 1000 meters above sea level (approximately 1300-1400 meters), such as around Mount Salak, Mount Gede, and Mount Pangrango, intensive weathering processes have produced volcanic residual soils with distinctive characteristics. These weathering products develop to considerable thickness and are characterized by the presence of amorphous minerals such as allophane and halloysite, formed from very fine-grained volcanic ash. The humid tropical climate with high annual rainfall in this region further accelerates chemical weathering, resulting in soils with very high natural water content, high Liquidity Index values, and mechanical behavior that is unique compared with non-volcanic residual soils.



**HOLOCENE VOLCANICS:** Active volcanics products comprise interbedded lava, breccia, tuff, and loose lahar deposit, generally andesitic to basaltic in composition, some dacitic, and containing pumice, volcanic ash, lapilli bombs.

Figure 1. Geological formation of study area

The geological map in Figure 1 indicates that the study area is part of the Holocene volcanic zone that remains geologically active. This explains why soil profiles in the region are dominated by residual soils derived from the weathering of young volcanic rocks, with textures ranging from fine-grained silty clay to coarse volcanic fragments of sand and gravel.

### 3.1. Field Soil Investigation Results

Figure 2 show the results field investigation, i.e., 4 SPT and 4 CPTu, showing the variation of penetration resistance with depth. Based on the drilling (core box sample shown in Figure 3) and SPT results, the subsurface soils at the project site were initially classified as silty sand, with SPT N-values generally less than 10 within the depth interval of 0–10 m, indicating a loose relative density. This interpretation is supported by grain size analysis (Figure 4) indicating around 60% sand content. However, from visual inspection of the split spoon samples in the core box, the samples appear partially aggregated and exhibit a degree of interparticle bonding rather than behaving as loose granular material. When handled manually, the material tends to break apart into granular particles, while simultaneously exhibiting a high moisture content, giving the impression of water surrounding the grains.

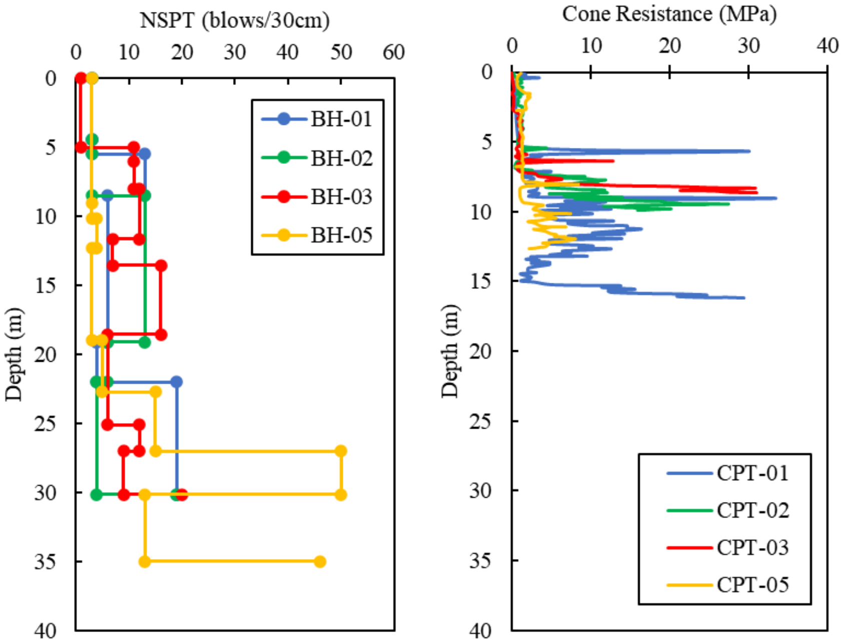


Figure 2. NSPT blows and cone resistance with depth.

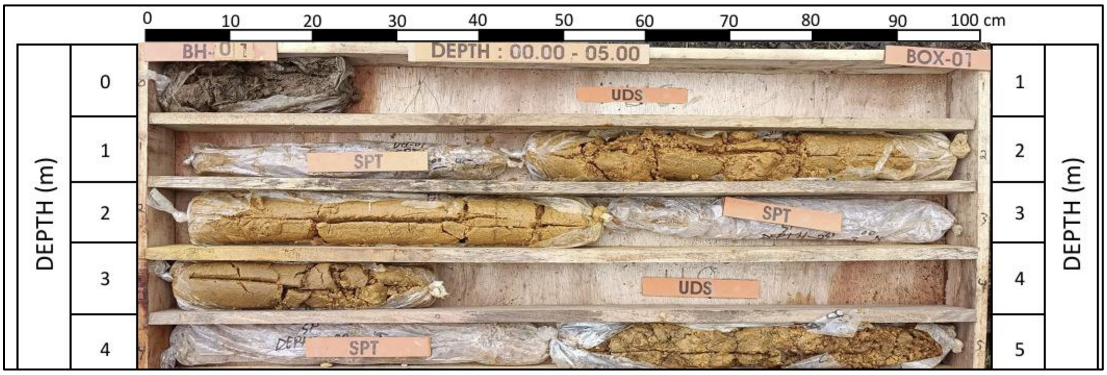


Figure 3. SPT core box samples

Further investigation using CPTu provided a different perspective on the soil behavior. Figure 5 shows the complete dataset of CPTu-1. CPTu-1 results indicate that the friction ratio (FR) exceeds 2% within the depth range of 0–7 m. This range of FR is commonly associated with fine-grained soils (Lunne et al., 1997), particularly clay, suggesting predominantly cohesive soil behaviour in the upper layer. Figure 6 presents the SBT classification plot, indicating that the CPTu-1 data within the depth range of 0–7 m predominantly fall within Zones 3 to 5, corresponding to clay to silty clay behaviour. With an average cone resistance (qc) of approximately 20 kg/cm² within 0–7 m interval. This corresponds to a medium stiff consistency when interpreted under undrained conditions

This interpretation contrasts with the coarse-grained indication from grain size analysis. The grain size analysis which shows 60% sand content is likely due to oven drying which clumps the fine particles to aggregates (Kroetsch & Wang, 2008). Kroetsch & Wang (2008) suggest that the oven-dried soil has to be broken as fine as possible, wash on a No. 200 sieve and redry using oven before sieving. The contrast between grain size analysis and CPTu highlights the difficulty of relying solely on lab tests to classify volcanic residual soils. The grain size analysis results highlight the sensitivity of these soils to oven drying, affecting the grain size distribution.

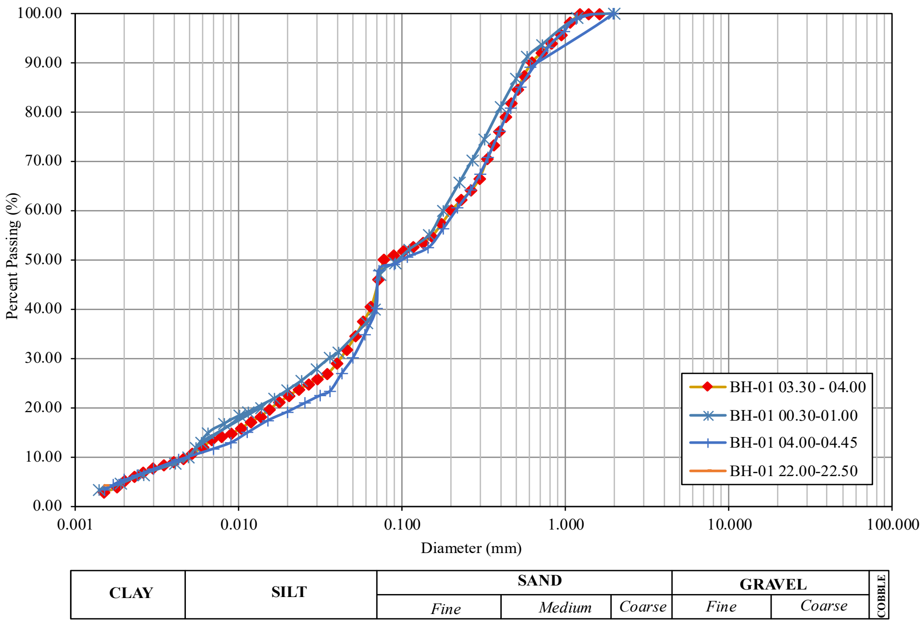


Figure 4. Grain size distribution.

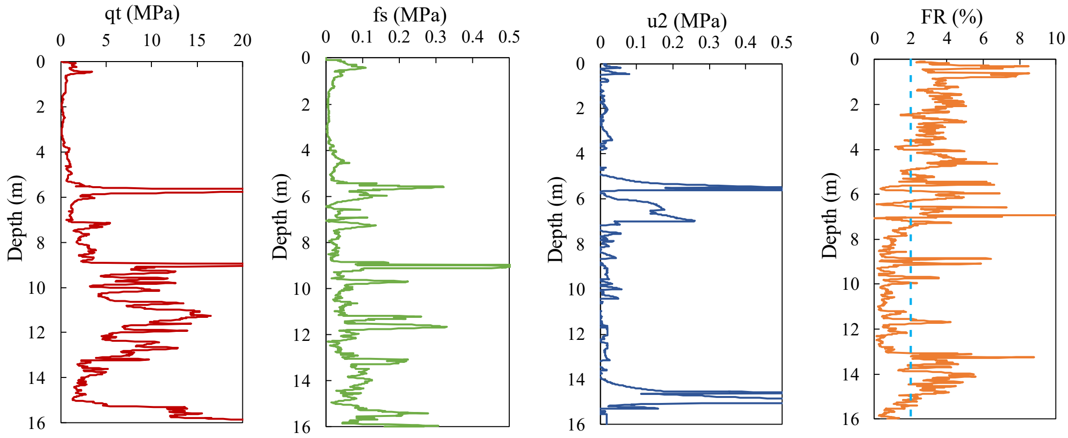
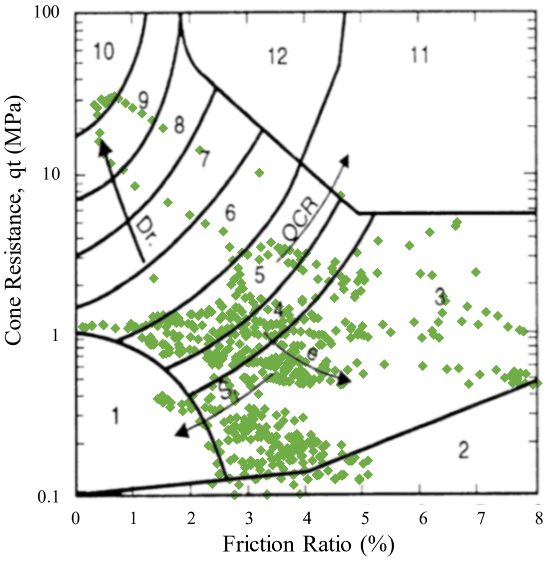


Figure 5. CPTu-1 results showing profiles of cone resistance (qt), sleeve friction (fs), pore pressure (u2), and friction ratio (FR).



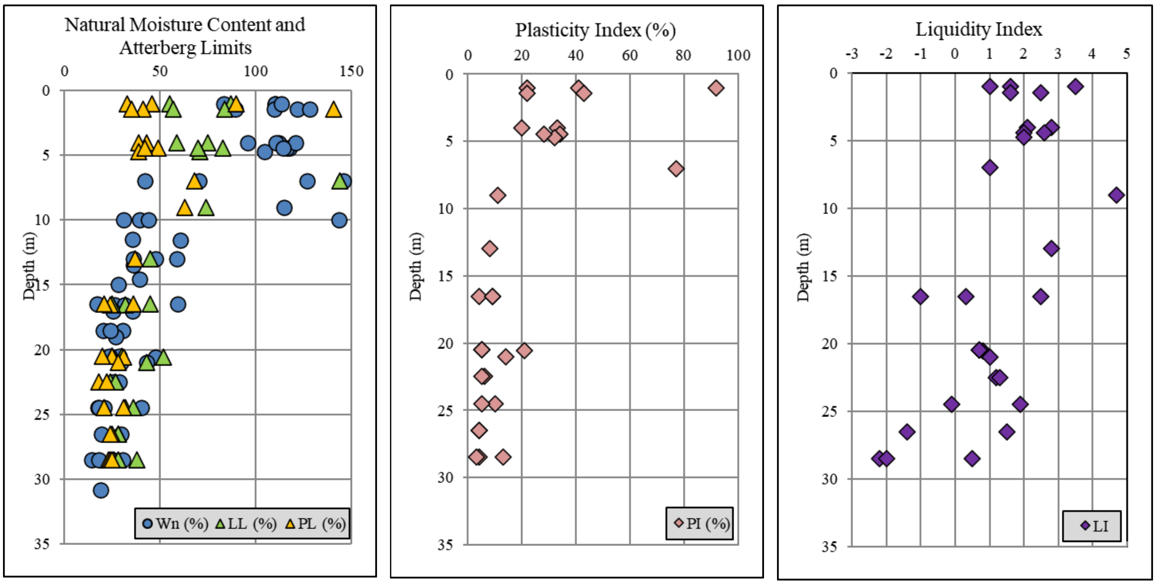
| Zone | Soil Behavior Type |
|---|---|
| 1 | *Sensitive fine grained* |
| 2 | *Organic material* |
| 3 | *Clay* |
| 4 | *Silty clay to clay* |
| 5 | *Clayey silt to silty clay* |
| 6 | *Sandy silt to clayey silt* |
| 7 | *Silty sand to sandy silt* |
| 8 | *Sand to silty sand* |
| 9 | *Sand* |
| 10 | *Gravelly sand to sand* |
| 11 | *Very stiff fine grained** |
| 12 | *Sand to clayey sand** |

*Overconsolidated or cemented

Figure 6. CPTu-1 SBT index indicating clay to silty clay soil

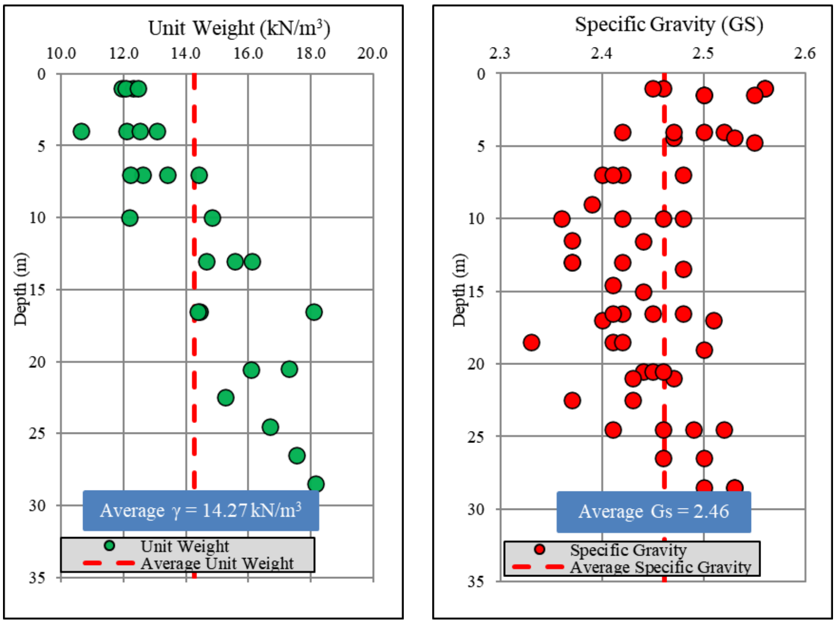
## 3.2. Laboratory Soil Investigation Result

The results of the laboratory testing for natural moisture content and the Atterberg limit are presented in Figure 7. The average natural moisture content is 61%, with values exceeding 100% at depths between 0–10 m. When compared with the Atterberg limits, it is evident that the natural moisture content within this depth interval is higher than the liquid limit (LL). This condition indicates that the soils in the upper 10 m are in a very soft state, approaching liquid-like behavior, with a Liquidity Index (LI) greater than 1. An LI value above unity implies that the soils in their natural condition have surpassed the liquid limit, reflecting very high sensitivity which are known to undergo significant loss of shear strength when disturbed. Figure 8 shows the index properties, namely unit weight and specific gravity. The average unit weight is 14.27 kN/m³, while the average specific gravity (Gs) is 2.46.



(a) (b) (c)

Figure 7. Soil laboratory test results: (a) Atterberg limits (b) Plasticity Index (c) Liquidity Index



(a) (b)

Figure 8. Soil laboratory test results: (a) unit weight and (b) specific gravity

Figure 9 presents the Cassagrande plasticity chart, which is used to compare the Atterberg test results from the study site with data from tropical residual soils previously classified by Wesley (1973). In this chart, in addition to the soil test results from the present study (red diamond symbols), historical data for Andosols (blue symbols) and Latosols (gray symbols) are also shown for comparison. This classification is important as it provides context regarding the mineralogy and mechanical behaviour of tropical residual soils originating from both volcanic and non-volcanic environments.

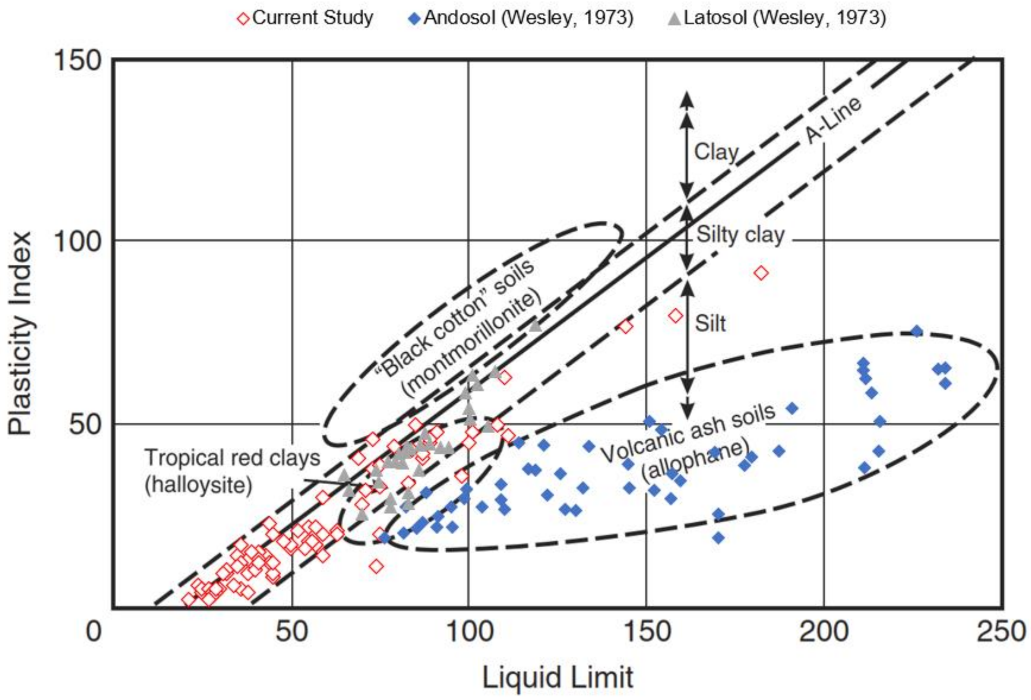


Figure 9. The plasticity chart of this study and tropical residual soils in existing literature

Most samples from the study site plot within the zone typically associated with tropical red clays (halloysite). This result is noteworthy because, from a geological perspective, the study area is situated at an elevation above 1000 m, where according to Wesley (2010), volcanic residual soils at such altitudes are generally still rich in allophane. In other words, the Atterberg test results indicate a halloysite tendency, whereas the local geological conditions suggest allophane dominance.

From a mineralogical standpoint, volcanic residual soils undergo progressive chemical weathering. The initial stage begins with fresh volcanic ash, which weathers into allophane. Over time, under humid tropical conditions, allophane transforms into halloysite. This process continues with the conversion of halloysite into kaolinite, subsequently developing into iron- and aluminium-rich sesquioxides, and ultimately forming hard laterite in the final stage. The results of this study may represent a transitional condition, in which allophane has partially transformed into halloysite due to intensive chemical weathering under humid tropical conditions. This is corroborated by soil characteristics such as high natural moisture content, a liquidity index (LI) greater than 1, and sensitivity typical of volcanic residual soils.

From a methodological perspective, differences in classification may also be influenced by the testing technique employed. Atterberg tests on volcanic residual soils were conducted using oven-dried samples, which are known to alter the microstructure of amorphous minerals such as allophane. This drying process can induce irreversible changes, causing soils that were originally plastic to appear non-plastic. Consequently, data that would have represented allophane may shift toward halloysite on the plasticity chart.

As shown in Figure 10, the Atterberg limit results obtained from oven-dried samples tend to be lower in liquid limit and plasticity index compared to samples which are air-dried (natural) condition. Previous studies (Wesley, 2010) have reported that oven drying may alter the microstructure of volcanic residual soils containing amorphous minerals such as allophane. The heating process causes irreversible changes that reduce the soil's plasticity, resulting in a leftward shift on the plasticity chart when compared to air-dried or natural samples. This shift indicates that the apparent reduction in plasticity is a testing artifact rather than a true representation of the in-situ soil behavior. Therefore, the Atterberg test results in this study not only provide a classification of plasticity indices but also imply an interaction between the natural mineralogical conditions and artifacts introduced by the testing method. This underscores the importance of careful interpretation of tropical residual soil index data and the methodology of soil laboratory tests, as differences in mineralogy (allophane versus halloysite) have significant implications for soil mechanical behaviour, particularly in terms of sensitivity and response to disturbance.

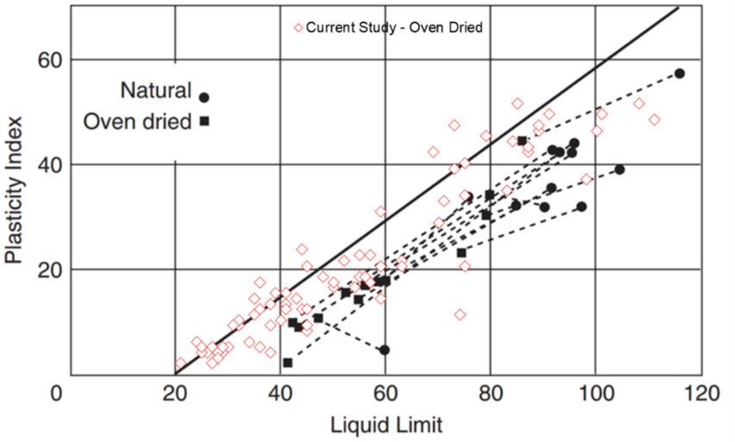


Figure 10 Effect of drying method on the Atterberg Limits (After Wesley, 2010)

Table 1 presents the residual soil database based on the Casagrande chart, summarizing data on site elevation, location, soil description, depth, and underlying rock type, as reported by Wesley (1973) and the present data.

Table 1 Residual soil database of Casagrande Chart (After Wesley, 1973)

| Site | Elevation | Location | Description | Depth of soil | Underlying rock |
|---|---|---|---|---|---|
| 1 | 750 m | 20 km east of Bandung on Sumedang road, km peg 21 | Reddish brown clay | 2–3 m | Conglomerate (andesitic) |
| 2 | 700 m | 15 km south of Bandung on Pangalengan road, km peg 20·4 | Reddish brown clay | About 3 m | Conglomerate (andesitic) |
| 3 | 50 m | 20 km south of Jakarta on Bogor road, km peg 24·8 | Reddish brown clay | At least 10 m | Tuffaceous sandstone |
| 4 | 100 m | 90 km east of Jakarta on Tjikampek–Purwakarta road, km peg 5 | Red clay | Not known; probably very deep | Not known; probably tuff |
| 5 | 1250 m | 10 km north of Bandung, approx. 150 m from Lembang on track to Tangkubanprahu | Dark yellowish brown clay | 2 m | Very fine-grained tuff |
| 6 | 1450 m | 25 km south of Bandung on Pangalengan road, km peg 39·9 | Light yellowish brown clay | At least 10 m | Probably ash |
| 7 | 1600 m | 30 km south of Semarang on access road to Mt. Telomojo microwave station | Yellowish brown clay | At least about 50 m | Ash |
| 8a | 1450 m | 28 km south of Bandung, at top of Tjipanundjang dam borrow pit | Yellowish brown clay | About 50 m | Ash |
| 8b | 1450 m | 28 km south of Bandung, at bottom of Tjipanundjang dam borrow pit | Yellowish brown clay | About 50 m | Ash |
| 9 | 1340 m | Mount Salak, Sukabumi<br>(Current study) | Yellowish brown clay | About 35 m | Conglomerate |

### 3.3. Field Observation Assessment

Field observations on excavated slopes in tropical residual volcanic soils reveal a distinctive characteristic. Several free-standing excavation cuts were identified at the site, with heights ranging from 5 to 12 meters as shown in Figure 11 & 12. The presence of vertical to near-vertical slopes capable of standing unsupported indicates that the in-situ soils possess a relatively high degree of natural cohesion, allowing them to maintain stability without immediate signs of sloughing or collapse.

(a) (b)

Figure 11. Free standing excavation cuts at the location adjacent to the site (a) about 12 meters (b) about 5 meters

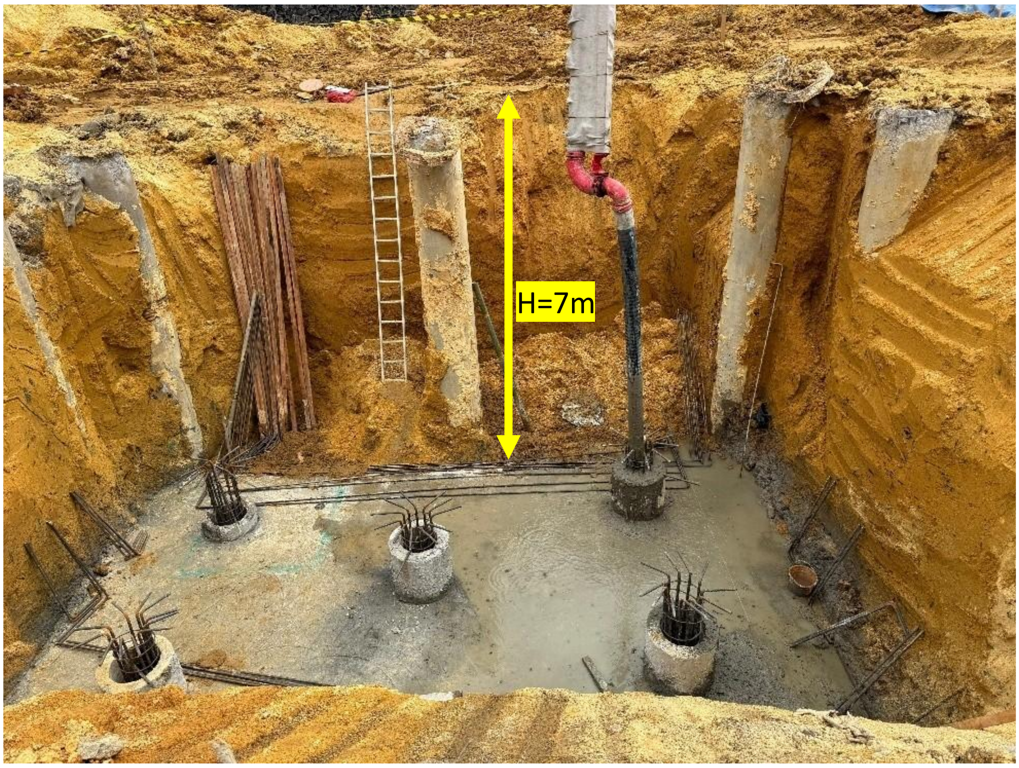


Figure 12. Example of deep excavation of residual soil

This phenomenon is not only influenced by the unsaturated condition above the groundwater table—where pore spaces are filled by both air and water due to the groundwater being located at approximately 15 meters below the surface—but is also reinforced by the natural cementation processes within the residual volcanic soils. Weathering and the formation of secondary minerals (such as iron and aluminium oxides) produce interparticle bonding that increases the soil's shear strength. This cementation plays a significant role in providing apparent cohesion, enabling near-vertical stable slopes with heights exceeding 10 meters to form.

### 3.4. Interpretation of Soil Shear Strength

Figure 13 presents an interpretation of the undrained shear strength (Su) based on field investigation using CPT and SPT as well as laboratory triaxial UU test results. The comparison shows that the laboratory results are more consistent with Su estimated from CPTu, whereas Su values derived from SPT tend to be underestimated even when using the correlation Su = 10N. This underestimation occurs because the SPT method inherently produces disturbed samples, which limits the accuracy of N-SPT correlations in representing the in-situ condition. The correlation among SPT, CPTu, and laboratory-derived Su values indicates that the degree of sample disturbance has a major influence on strength interpretation. In sensitive volcanic residual soils, such disturbance causes a considerable reduction in the measured strength, making CPTu a more reliable method for capturing representative in-situ undrained shear strength, while SPT-based results tend to be overly conservative.

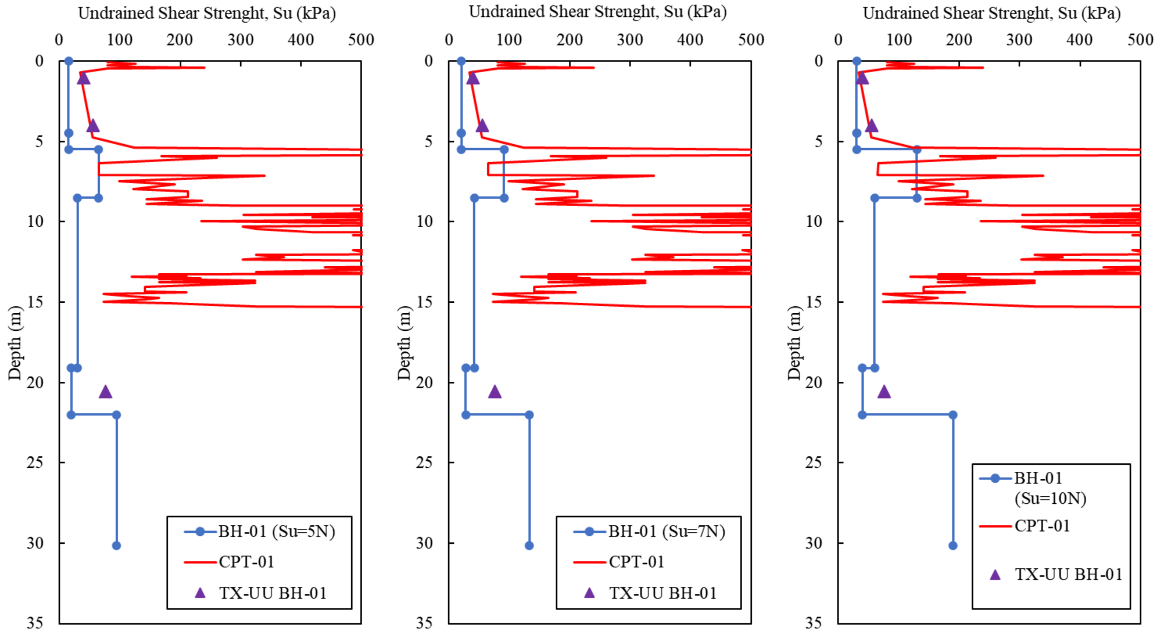


Figure 13. Comparison of undrained shear strength SPT, CPTu, and triaxial UU

## 4. IMPLICATIONS & DISCUSSIONS

The characteristics of residual soils are strongly influenced by the physical and chemical properties of their parent rock. The handling and treatment of residual soil samples also significantly affect the degree of weathering and the strength parameters obtained. Therefore, when determining engineering parameters of residual soils, several important notes should be considered, given their distinct behavior compared to ordinary sedimentary soils:

1. **Sample handling:** It is essential to ensure that the tested samples remain as undisturbed as possible and are managed properly to prevent changes in the soil's physical and chemical properties. For example, testing residual soil samples using air drying method is

recommended, as oven-drying can alter both the mineralogical composition and the soil structure, which may lead to misinterpretation of soil classification, shear strength and grain size distribution.

2. **Field testing:** Field investigations should employ testing methods that minimize sample disturbance, such as CPT. This is supported by the observation that Su values derived from CPT are generally closer to laboratory test results compared to those estimated from SPT. Consequently, when selecting design shear strength parameters for residual soils, higher reliability is achieved by prioritizing CPT and laboratory triaxial tests, while SPT-based correlations should be treated with caution due to their tendency to underestimate the strength due to sample disturbance.
3. **Soil identification:** One of the key indicators of residual soil is its particle size distribution obtained from sieve analysis. Residual soils commonly exhibit a *gap-graded* distribution, which is a result of non-uniform weathering processes acting on the parent material. It should also be noted that oven-drying can result in apparent dominance of sand-size grains.

In summary, careful attention to sample handling, appropriate selection of field and laboratory testing methods, and recognition of the distinct particle size distribution are crucial for accurate engineering behavior characterization of residual soils. These considerations are critical in ensuring that the chosen shear strength parameters are both representative and reliable for design purposes.

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