Correlation of Undrained Shear Strength and Liquidity Index of Fine-Grained Soils in West Java, Indonesia

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Abstract. The undrained shear strength of fine-grained soils is an important property in geotechnical engineering. However, the process of determining undrained shear strength can be challenging. Hence, the correlation of undrained shear strength with other soil properties needs to be established. Several studies have estimated undrained shear strength using the liquidity index. In the current study, we aim to find the best correlation of undrained shear strength and liquidity index of fine-grained soils in West Java, Indonesia at various water contents using the form of correlation of undrained shear strength and liquidity index and also factors influencing the undrained shear strength. The values of undrained shear strength and liquidity index are obtained by laboratory test and data collection from previous studies of soils in West Java. Results show a good linear relationship between the logarithmic value of undrained shear strength and liquidity index for 173 variations of soil samples. We also can conclude that the undrained shear strength of fine-grained soils is controlled by the proportion of finer grains presence and also the plasticity of the soils.

1. Introduction
Undrained shear strength, defined as the maximum shear stress that soil can withstand in undrained conditions, is an important parameter in geotechnical engineering. It affects the bearing capacity of foundation, slope stability, retaining of wall design, and indirect pavement design [1]. It can be determined by several processes, but these processes are time consuming and difficult. Therefore, a fast and easy way to estimate undrained shear strength is needed.

The undrained shear strength of fine-grained soils is related to the water content of soils. Water in fine-grained soils can affect the behavior of soils; it is scaled against the standard of Atterberg limits, such as plastic limit and liquid limit [1]. Liquid limit (LL) is the water content at which the soil begins to flow as a viscous liquid, whereas plastic limit (PL) is the water content when the material of the soil begins to become plastic [2]. LL and PL serve as the upper and lower limits of the water content of the plastic state of soil, respectively. They determine many soil properties, such as undrained shear strength (cu). Liquidity index (LI), which is defined by Equation (1), has been studied by many researchers and is correlated with the undrained shear strength of soils.

\[ LI = \frac{w_{PL}}{LL - PL} \]  

Wroth and Wood [3] proposed the commonly used Equation (2) as follows:
\[ c_u = 1.7 \times 10^2 (1 - \frac{LL}{PL}) \text{ kPa} \]  \hspace{1cm} (2)

Wroth and Wood in [3] proposed that \( LL \) and \( PL \) correspond to a fixed strength in the ratio of 1:100. Equation (2) is re-written to Equation (3) [4] as

\[ c_u = c_L R_{MW}^{(LL)} \]  \hspace{1cm} (3)

where \( c_L \) is the undrained shear strength at \( LL \) and \( R_{MW} \) is the ratio of strength at \( LL \) and \( PL \). A research in [5] proposed that the average \( R_{MW} \) value is indeed 100 as provided by Wroth and Wood [3]. While another researcher suggested that the average \( R_{MW} \) value is 35 [6].

The undrained shear strength of fine-grained soils is affected by other factors besides the presence of water, such as grain size and the consistency of soils. Increasing proportion of smaller particles influences the raise of cohesion which leads to higher undrained shear strength. Plasticity also plays an important role, soils with high plasticity bind more water which lowers the value of undrained shear strength [7]; while plasticity of fine-grained soils is a function of clay fraction and activity [8]. The strength is also influenced by the type of clay mineral presence. The undrained shear strength is a result of net attractive force between clay particles and friction from coarse particles and also viscous shear resistance contributed by diffuse double layer [9].

This study aims to determine the correlation of \( c_u \) and \( LI \) of fine-grained soils in West Java, Indonesia in the same form of Equation (3), including the identification of the values of \( c_L \) and \( R_{MW} \) and also some factors influencing those values.

2. Method and Materials

2.1. Laboratory Test

Laboratory tests are conducted to achieve the aim of the study. The main laboratory test used is a Fall Cone Penetrometer test. The data are divided into two groups. The first group comprises the sample from Bandung as primary data with 91 variations of water content. The latter group is a set of data collected from our previous research at West Java with 82 variations of water content.

2.1.1. Sample Preparation

Seven samples of fine-grained soils from West Java are collected for testing (Table 1). The samples are then tested to obtain their natural water content (\( w \)) and unit weight (\( \gamma \)).

2.1.2. Atterberg Limits

All the soils are tested for the Atterberg limits. \( LL \) is determined by Casagrande’s percussion method, as specified by ASTM D4318 [10]. \( PL \) is determined by thread rolling method, also as specified by ASTM D4318. The soil type classification used is USCS, and the main types for the samples are CH (clay with high plasticity), CL (clay with low plasticity), MH (silt with high plasticity), and ML (silt with low plasticity).

| Soil    | Water Content [\%] | Unit Weight [kN/m\(^3\)] | Plastic Limit | Liquid Limit | Plasticity Index | Soil Type (USCS) |
|---------|---------------------|---------------------------|---------------|--------------|------------------|------------------|
| Sample 1| 17.36               | 21.70                     | 25.63         | 59.49        | 33.86            | CH               |
| Sample 2| 11.66               | 23.02                     | 24.02         | 40.32        | 16.30            | CL               |
| Sample 3| 47.78               | 17.96                     | 34.34         | 40.73        | 6.39             | ML               |
| Sample 4| 55.35               | 16.17                     | 48.99         | 77.30        | 28.31            | MH               |
| Sample 5| 70.40               | 16.36                     | 77.11         | 115.8        | 38.69            | MH               |
| Sample 6| 0.68                | 25.97                     | 28.30         | 53.60        | 25.30            | CH               |
| Sample 7| 15.54               | 16.66                     | 67.35         | 100.41       | 33.06            | MH               |
2.1.3. Undrained Shear Strength
The undrained shear strengths at various levels of water content are determined by the Fall Cone Penetrometer test following BS1377 [11], with 80 g cone and 30° cone angle. The undrained shear strength is derived [12] in Equation (4).

\[ c_u = K \frac{mg}{d^2} \]  

(4)

where \( K \) is the cone factor, \( m \) is cone mass, \( g \) is acceleration of gravity, and \( d \) is cone penetration. The value of \( K \) is 0.867 for a British standard cone [13].

2.2. Data Collection
The data of \( L_I \) and \( c_u \) at various levels of water content are collected [14] [15] [16] to improve the accuracy of the study. As shown in Table 2, 12 samples are collected from West Java. Kaolin, Bentonite, and other fine-grained soils are collected from Karang Mukti, Parakan Muncang, Parung Ponteng, Gedebage, and Rancaekek. The main types of soil in this region are CH and MH.

| Soil            | Plastic Limit | Liquid Limit | Plasticity Index | Soil Type | References |
|-----------------|---------------|--------------|------------------|-----------|------------|
| Karang Mukti    | 28.08         | 81.87        | 53.79            | CH        | [14]       |
| Kaolin          | 38.45         | 68.00        | 29.55            | MH        | [15]       |
| Parakan Muncang | 29.28         | 66.64        | 37.36            | CH        | [15]       |
| Kaolin          | 30.47         | 51.85        | 21.38            | MH        | [16]       |
| Bentonite       | 57.45         | 87.03        | 29.58            | MH        | [16]       |
| Parung Ponteng  | 34.59         | 50.40        | 15.81            | MH        | [16]       |
| Gedebage        | 53.28         | 86.22        | 32.94            | MH        | [16]       |
| Rancaekek 1.5–2 m | 38.68       | 93.55        | 54.87            | CH        | [16]       |
| Rancaekek 2–2.5 m | 31.58       | 80.32        | 48.74            | CH        | [16]       |
| Rancaekek 3–3.5 m | 39.53        | 74.40        | 36.87            | CH        | [16]       |
| Rancaekek 3.5–4 m | 32.64        | 78.54        | 45.90            | CH        | [16]       |
| Rancaekek 4–4.5 m | 36.59        | 82.51        | 45.92            | CH        | [16]       |

3. Results and discussion
Correlation of \( c_u \) and \( L_I \)
By plotting \( c_u \) and \( L_I \) from the data in Table 1 and 2 into Figure 1, we produce a regression line as presented in Equation (5):

\[ c_u = 109.54 e^{-3.732 L_I} \]  

(5)

From Equation (5), average \( c_u \) at \( LL (L_I = 1) \) is 2.62 kPa (from a range of 0.35 to 19.79 kPa), and average \( c_u \) at \( PL (L_I = 0) \) is 109.55 kPa (from a range of 20 to 600 kPa). Therefore, the average \( R_{MW} \) or ratio between \( c_u \) at \( LL \) and \( c_u \) at \( PL \) becomes 42. The value of \( c_u \) at \( LL \) for these data is near to 2.65 kPa [13]. However, the value of \( c_u \) at \( PL \) for this finding is as low as 42%, which is lower than the value proposed before [3]. Equation (5) can be rearranged into the same form presented before [4] as in Equation (6):

\[ c_u = c_k R_{MW}(1-L_I) = 2.62 \times 42^{(1-L_I)} \text{kPa} \quad (0 < L_I < 1) \]  

(6)
If the soils are classified into groups of clay soils and silt soils, we can find another correlation as shown in Figure 2.

**Figure 1.** Relationship Between Undrained Shear Strength \((c_u)\) and Liquidity Index \((LI)\)

**Figure 2.** Relationship Between Undrained Shear Strength \((c_u)\) and Liquidity Index \((LI)\) for Clays and Silts
The average regression lines show us that the clay soils have higher undrained shear strength than the silt soils, as presented in Equation (7) and (8).

\[ c_{u, \text{clay}} = 165.83 \times e^{-4.239 \text{LI}} \]  
\[ c_{u, \text{silt}} = 48.99 \times e^{-2.938 \text{LI}} \]  

From Equation (7), we get that average \( c_u \) at \( LL (\text{LI}=1) \) is 2.67 kPa (with a range of 0.37 to 19.19 kPa) and average \( c_u \) at \( PL (\text{LI}=0) \) is 165.83 kPa (with a range of 55 to 500 kPa) for clays. Therefore, the average \( R_{MR} \) for clay soils is 63. While from Equation (8), we get that \( c_u \) at \( LL (\text{LI}=1) \) is 2.60 kPa (with a range of 0.65 to 10.44 kPa) and average \( c_u \) at \( PL (\text{LI}=0) \) is 48.99 kPa (with a range of 16 to 150 kPa) for silts. So, the average \( R_{MR} \) for silt soils is 19. Equations (7) and (8) can be rearranged into the form [4] of Equations (9) and (10):

\[ c_{u, \text{clay}} = 2.67 \times 63^{(1-LI)} \text{kPa} \]  
\[ c_{u, \text{silt}} = 2.60 \times 19^{(1-LI)} \text{kPa} \]  

We also differentiate the types of soil based on the plasticity of the soils and find a good connection. From Figures 3 and 4, we can see that soils with lower plasticity hold higher undrained shear strength both for clays and silts.

From Figures 3 and 4, the correlation of undrained shear strength and liquidity index of CH, CL, MH, and ML soils can be presented by Equations (11) to (14):

\[ c_{u, \text{CH}} = 2.28 \times 69^{(1-LI)} \text{kPa} \]  
\[ c_{u, \text{CL}} = 15.30 \times 17^{(1-LI)} \text{kPa} \]  
\[ c_{u, \text{MH}} = 2.01 \times 28^{(1-LI)} \text{kPa} \]  
\[ c_{u, \text{ML}} = 7.94 \times 8^{(1-LI)} \text{kPa} \]
4. Conclusion
On the basis of the experimental results and the collection of experimental results of previous studies of fine-grained soils in West Java, a good correlation exists between undrained shear strength and liquidity index for 173 variations of water content.

The relation between undrained shear strength and liquidity of fine-grained soils in West Java has an undrained shear strength ratio of 42 for soil in plastic state. This value is in the range of 35–100 from previous research.

Factors affecting the undrained shear strength of fine-grained soils are the percentage of fines and plasticity. Soils with higher composition of finer grains (clays) have higher undrained shear strength than soils with lower composition of finer grains (silts). Soils with lower plasticity have higher undrained shear strength because soils with higher plasticity binds more water which decreases the soil strength.

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