Physical Characteristics of the Compressibility of Saturated Cohesive Soil

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Abstract. Water content and liquid limit are basic physical properties in saturated cohesive soils. Through the statistical analysis of compression index and these two physical properties, trends showed that compression index increases with increasing water content and liquid limit. Very loose and soft saturated cohesive soils with high water content have high compressibility; however, very stiff and hard saturated cohesive soils have low compressibility. Based on these tests, the correlations of compression index and physical properties were established for soils in China. These correlations provide a good approach to predict compression index based on physical properties and can be used for geotechnical parameter analysis.

Keywords. Saturated Cohesive Soil; Water Content; Liquid Limit; Compression Index; compressibility; Physical Characteristics

1. Introduction
Soil compressibility is the property where volume decreases when soil is compressed, possibly because of pore compression. Soil compressibility directly affects the deformation of foundations. An E-log p curve is often used to analyze and study the influence of stress history on soil compressibility [1-7], and this curve is significant for the settlement calculation of buildings.

When the soil is compressed with lateral constraints, the compression curve, e-log p, is a straight line in the range greater than the preconsolidation pressure, and the soil compression index (Cc) is the slope of this section of the graph (as shown in Figure1), which is an index of the settlement amount of the cohesive soil foundation.

![Figure 1. e-logp Curve](image)

Soil compressibility increases with increasing Cc. A Cc value for low compressibility soil is generally <0.2, while a Cc value of >0.4 is typically of a high compressibility soil [8-9].

Soil pore compression indicates that excess pore water pressure decreases and effective stress for saturated soil increases, and this compression specifically reflects the decrease in water content and
porosity (porosity ratio) in the physical characteristics of soil. The water content indicates the relationship between pore water pressure and effective stress in the historical period. With soil compression, increases effective stress lead to decreases in water content and compressibility. Moreover, the soil plasticity may affect the soil compressibility. The liquid limit is an Atterberg limit, and it is the water content at which the behavior of a clay-filled soil changes from the plastic state to a flowing state. With the increased liquid limit, the fine content increases and the soil becomes more plastic. Moreover, the soil may endure longer periods in the consolidation process to obtain the same degree of consolidation. Therefore, a study of the relationship between water content ($W_n$), liquid limit ($W_L$), and compression index ($C_c$) in saturated clay can provide a method to evaluate compressibility by physical indexes. This is a better reference for domestic engineering. According to Terzaghi in 1995 [7] and Terzaghi and Peck in 1967 the correlation between the liquid limit and compression index was studied. The compression index was calculated by the liquid limit; however, there was an error of plus or minus 30%. In 1981, Koppula studied the correlation between water content and compression index using 109 data points, and then in 1986, Koppula calculated the compression index using water content and liquid limit for all clays. At present, the compressibility indices used in China primarily include compressibility coefficient and compression modulus. However, these indices cannot reflect the overall compressibility of soil and the influence of stress history on soil compressibility because both indices are calculated based on different loading intervals. In general, the compression indices and pre-consolidation pressure can be used to calculate the settlements, which allows for the defects to be more obvious. Moreover, it is not economical to conduct a large number of oedometer tests in small- and medium-sized projects because of the scarcity and long times to complete such tests. Lin (1994) suggested relevant correlations of compression index with physical properties, including water content and liquid limit. However, the reliability is poor because the difference between the predicted and measured compression indices can be up to 30%.

In this study, test results were analyzed to obtain relationships between compressibility and physical properties. These results primarily include compression indices of saturated clays and the corresponding water contents and liquid limits retrieved in domestic geotechnical investigation projects over the past 20 years.

2. RESEARCH METHOD

One hundred seventy-two geotechnical reports for projects were used. Three hundred forty-four compression indices and 1233 water contents and liquid limits were analyzed based on tests on different types of clay-filled soils, including very soft, soft, firm, stiff, very stiff, and hard clay. Relationships between compression index and physical properties (water content and liquid limit) were obtained.

3. BASIC CHARACTERISTICS OF WATER CONTENT, LIQUID LIMIT, AND COMPRESSION INDEX

3.1 Water Content of Saturated Clay

Figure 2 shows the vertical distribution of 1233 water contents. The water content ranged from 13.5% to 118%, including very soft to soft clay with large water contents, firm to very stiff clay with medium water contents, and hard clay with low water content.
3.2 Liquid Limit of Saturated Clay
A total of 1233 liquid limits were selected, including very soft to soft clay and firm to hard clay, as shown in the straight distribution of Figure 3. The bottom and top limits of cohesive soils are generally 24% and 92.4%, respectively, with the most typical values between 30% and 60%. Saturated cohesive soils from low to high liquid limits are included.

3.3 Compression Index of Saturated Clay
A total of 344 compression indexes were collected, including very soft to hard saturated clay, as shown in Figure 4. The compression index of cohesive soil was generally 0.04 at the lower end of the range and 1.1 at the top end of the range with most values between 0.1 and 0.9, and includes all types of saturated cohesive soils from low to high compression.

3.4 Parameter Reasonableness
Clay-filled soils with different stiffness states were analyzed, including very soft, soft, firm, stiff, very stiff, hard, and very hard. Moreover, the ranges of physical properties (water content and liquid limit)
and compression indices were large. To conclude, the analyzed saturated clay-filled soils can comprehensively represent all types of states, and the research is reasonable and representative.

4 RELATIONSHIP BETWEEN WATER CONTENT AND COMPRESSION INDEX

As shown in Figure 5, a scatter diagram is drawn with the water content as the abscissa and the corresponding compression index as the ordinate. From the analysis of the distribution of each point on the figure, the compression index increases with increase in water content. When the water content reaches 40%, the compression index coincides with 0.4. Similarly, as water content increases, the compression index increases. In practical engineering, clay-filled soils with water contents of >40% are normally composed of very soft to soft clay and exhibit high compressibility. Moreover, clay-filled soils with water contents not >20% comprise hard clay and show low compressibility. Furthermore, a corresponding compression index of <0.2 shows low compressibility.

To conclude, the water content can be used to predict compression index of soil. Based on the curve fitting (Figure 5), a natural logarithmic correlation can be used to obtain a better performance. The correlation equation is shown as follows:

\[ C_c = 0.3485 \ln(W_n) - 0.9038 \]  

The \( R^2 \) value of the formula is 0.84, which shows good performance and availability of the formula.

![Figure 5. Scatter Diagram of Compression Index and Water Content](image)

5 RELATIONSHIP BETWEEN LIQUID LIMIT AND COMPRESSION INDEX

As shown in Figure 6, taking the liquid limit as the abscissa and the corresponding compression index as the ordinate, the scatter graph is drawn. In analyzing the distribution of each point on the graph, it shows the rule that the compression index increases from low to high as the liquid limit increases from low to high. When the liquid limit reaches 43%, the compression index reaches 0.4. As the liquid limit increases, the compression index increases. In practical engineering, if the liquid limit is >40%, the soil is saturated soil with a high liquid limit, the fine grain content is high, and the compression consolidation time is long. These characteristics occur most readily in very soft, soft, and firm clay soils. Soils with high compressibility typically exhibit a corresponding compression index of >0.4. When the liquid limit decreases to 33%, the compression index decreases to 0.2. As the liquid limit continues to decrease, the compression index continues to decrease. In practical engineering, soil with a liquid limit of >40% is low liquid limit soil, with less fine grain content, fast consolidation time, and
low compressibility. The corresponding compression index is <0.2, which is the performance of low compressibility.

Figure 6 shows the compression index has a relatively linear relationship with liquid limit. Through trend fitting, the distribution shows good linear correlation, thus forming a linear curve of the compression index and liquid limit, and the correlation formulas of the two are obtained as follows:

\[ C_c = 0.018W_L - 0.3872 \]  

The \( R^2 \) value of the formula is 0.84, which shows good performance and availability of the formula.

Figure 6. Scatter Diagram of Compression Index and Liquid Limit

6 CORRELATION BETWEEN LIQUID LIMIT AND WATER CONTENT

The corresponding liquid limit is related to the water content. With increasing liquid limits, the grain content is finer, the plasticity of the soil is increased, the porosity is greater, and the water content variation is greater. As shown in Figure 7, a scatter diagram is drawn with the water content as the abscissa and the liquid limit as the ordinate. Overall, it still shows the following rule: when the water content changes from less to more, the liquid limit changes from small to large.

However, the change in water content is not only related to the limit water content of soil, it is affected by the changes in pore water pressure, and effective stress under overlying pressure in geological history. Through trend fitting, the power correlation curve of liquid limit and water content is formed, and the correlation formulas of the two are obtained as follows:

\[ W_L = 10.474 \left( W_n \right)^{0.3788} \]  

The correlation coefficient, \( R^2 \), of the formula is 0.71, which has a general correlation and the usability of the formula is medium.
7 ENGINEERING APPLICATION

Based on the test results of compression indices, water contents, and liquid limits of saturated clay-filled soils in three projects, the compression indices are calculated using Eqs. (1) and (2) in this study and other equations used throughout the literature. As shown in Table 1, the predicted results based on different equations were compared and evaluated.

| Soil Type | 1 (soft clay) | 2 (firm clay) | 3 (hard clay) |
|-----------|---------------|---------------|---------------|
| Liquid Limit (%) | 56.4 | 42.7 | 34.5 |
| Water Content (%) | 85 | 35 | 21.3 |
| Compression Index | 0.638 | 0.398 | 0.203 |
| Formula 1 \( C_c = 0.3485 \ln(W_n) - 0.9038 \) | 0.644 | 0.335 | 0.162 |
| Formula 2 \( C_c = 0.018W_L - 0.3872 \) | 0.645 | 0.381 | 0.239 |
| Koppula [6] \( C_c = 0.0093W_n \) | 0.790 | 0.325 | 0.198 |
| Lin Zongyuan [9] \( C_c = 0.54(2.6W_n/100 - 0.35) \) | 1.000 | 0.302 | 0.110 |
| Lin Zongyuan [9] \( C_c = 0.009(W_L - 10) \) | 0.418 | 0.294 | 0.220 |

Based on Table 1, it can be concluded that, for soft clay, the compression index obtained from the two formulas derived in this study is slightly different from that obtained from the laboratory test, but the overall consistency is good. Furthermore, Koppula’s formula was used to calculate the compression index, and the values of firm clay and hard clay were similar to those calculated by the laboratory test and the two formulas. The above analysis shows that the two formulas obtained in this study are reliable and applicable and can be used to estimate geotechnical index. Moreover, note that the compression index of soft clay calculated by Koppula's formula is ~20% more than the results of this study and the actual laboratory test, indicating that Koppula’s empirical formula is not suitable for domestic soft soil layers.

Similarly, the compression index calculated by the formula suggested by Lin (1994) based on water content is quite different from the results of the laboratory test, even exceeding 30%, which is indicative of poor applicability.

8 CONCLUSIONS

(1) The compression indices of saturated clay-filled soils are natural logarithmically correlated with water content. Moreover, the compression index increases with increasing water content. Based on the behavior of different types of soil, the soil with high water content can possess high compressibility.
(2) The compression index is linearly correlated with liquid limit and it increases with the increase of liquid limit. In general, soils with high liquid limits show high compressibility.

(3) Correlations of compression index and physical properties (water content and liquid limit) might be applied to the saturated clay-filled soils in China.

(4) In this study, correlations of compression index and physical properties (water content and liquid limit) can be applied to non-weak saturated clay-filled soils abroad, but correlations with soft saturated soil need further study.

(5) In this study, quantitative relationships between water content, liquid limit, and compressibility of saturated clay were established, which can be used in the analysis of geotechnical parameters.

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