Study on the geometry and spatial distribution characteristics of physical and mechanical indexes of soft clay

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Abstract. The engineering characteristics of soft clay vary depending on its formation conditions and geological evolution. This study explored the empirical relationships and parameter predictions among indexes of the physical and mechanical properties of soft clay based on its geological origin, sedimentary characteristics, and distribution. In combination with statistical theory, the distribution characteristics and rules of the physical and mechanical properties indexes of soft clay were discussed and the correlation between each index was investigated. Results revealed reasonably small variability of certain physical indexes, such as density, specific gravity, plastic limit, and liquid limit, whereas the coefficient of variation of mechanical indexes was large. The minimum (maximum) values of physical (mechanical) indexes were observed in fluvial and lacustrine sedimentary soft clay or urban dredging soft clay, whereas the maximum (minimum) values were mostly observed in marine sedimentary soft clay. The physical and mechanical indexes of soft clay exhibit reasonable correlation and unknown parameters can easily be estimated using linear regression. However, the direct shear test was affected by the material’s regional characteristics; thus, mechanical indexes with poor correlation should be regarded as independent random variables for the parameter prediction. These findings improve understanding of the application of soft clay in engineering.

Keywords: Geometry and spatial distribution characteristics, physical indexes, mechanical indexes, soft clay

1 Introduction
Soft clay is a geological product that has changed over millions of years in terms of geography,
climate, and the sedimentary environment due to long-term geological action. Soft-clay-like soft soils are widely distributed in China, and approximately one-quarter of China’s coastline is classified as soft clay coast. Large areas with soft clay foundations are also created annually through reclamation and dredging activities\cite{1}. Different formation conditions and geological evolution have a significant impact on the engineering characteristics of soft clay\cite{2-4}, and the physical and mechanical indexes of soft clay samples can exhibit irregularities, even if the samples are obtained from the same borehole. Therefore, conducting statistical analysis on soft clay from different areas is critical to reveal the inherent laws of its physical and mechanical properties, and improve physical and mechanical parameter selection accuracy.

Statistical analyses of soil property parameters have been studied since the mid-twentieth century\cite{5}. Lumb was one of the first to investigate the variability of soil property indexes, which led to the idea of spatial variability\cite{6}. Subsequently, Vanmarcke established a soil-profile random field model and described the spatial variability of soil properties parameters using the correlation distance\cite{7}. Matsuo and Asaoka found that sampling disturbance and the inherent soil variability cause inconsistency in the probability model of the undrained strength of saturated clay\cite{8}. Zhang et al. studied the performance law of soil property index variability based on random field theory, introduced a trend function for the soil property index structure and proposed a statistical method for index variability\cite{9}.

The soft clay physical and mechanical indexes reflect the physical and mechanical properties that often influence and correlate with each other. The correlation coefficient can be used to describe the degree of interaction and correlation between different soft clay physical and mechanical properties. Geotechnical engineers have explored the empirical relationships and parameter predictions regarding soil physical properties. Skempton and Jones first obtained the linear relationship between the compression index ($C_s$) and the liquid limit ($W_L$) of remolded soil in 1944\cite{10}. Further, Terzaghi and Peck obtained a linear relationship between the $C_s$ and $W_L$ values of normally consolidated clay in 1967, which demonstrated an excellent correlation when the value of $W_L$ reached $110\%$\cite{11}. Nagaraj and Murthy discovered a linear relationship between $e/e_L$ and $I_{pd}$ based on the Gouy–Chapman diffusive electric double layer theory, theoretically deduced and explained the rationality of Skempton’s empirical formula ($C_s = W_L$), theoretically evaluated the existing empirical relationship of $C_s$, and proposed a new empirical relationship between normally consolidated and overconsolidated remolded soil\cite{12-14}. Anbazhagan et al. conducted 202 groups of surface wave tests and standard penetration tests in 25 locations and found an inverse correlation between the void ratio and standard penetration values through a comparative analysis of the void ratio, shear wave velocity data, and standard penetration values\cite{15}. Asem established a prediction model for soft rock deformation modulus and strength characteristics based on field test data\cite{16}. Statistical analyses of the variability and correlation of physical and mechanical parameters of cohesive soils in different regions have been conducted in several other research\cite{17-20}.

In comparison with the increase in the number of soft soil projects due to recent developments in sampling, handling, sample preparation, testing, and other related aspects, laboratory-based statistical research on soft clay and its engineering properties are limited, and systematic analysis of relevant geological survey data accumulated in various projects is insufficient. Therefore, this study investigated the origins, sedimentary characteristics, and distribution of soft clay in China. The principal indexes of soft clay physical and mechanical properties were analyzed using statistical theory, the distribution characteristics and laws of each index were investigated, and the correlation between each index was determined specifically to obtain research knowledge regarding soft clay’s use in dam engineering.

2 Distribution and sources of statistical data

Areas of soft soil (i.e., soft clay and muddy clay) in China are concentrated primarily in the Bohai Bay, Yangtze River Delta, Zhejiang and Fujian coastal areas (and certain other coastal areas), and in urban areas such as the cities of Wuhan and Kunming along major rivers (Figure 1)\cite{21}. The mineral
composition, sedimentary environment, and burial depth of the soft clay in these different areas vary significantly.

Test data from 105 typical soft clay projects in China were sorted and analyzed after a literature search. The projects included several practical developments regarding water conservancy, construction, transportation, ports, and reclamation. Statistical analysis of 322 groups of physical and mechanical test data of soft clay revealed soft soil in the studied areas. The statistical data are general.

![Figure 1. Regional distribution of typical soft clay in China](image)

3 Calculation of variability and correlation of geotechnical parameters

To compare the dispersion degree of each data group and eliminate the influence of different units or means, or both, on the variation degree comparison of two or more data elements based on probability and statistical theory\cite{22}, the samples’ mean value, $\mu$, standard deviation, $\sigma$, and coefficient of variation, $\delta$, were used as evaluation criteria of the variability of geotechnical parameters to determine the variability and dispersion of the physical and mechanical indexes of soft clay. Assuming that $x_1, x_2, \ldots, x_n$ are variables, the average value $\overline{x}$, $\sigma$, and $\delta$ can be calculated using Eqs. (1)–(3), respectively:

Sample mean:

$$\overline{x} = \frac{x_1 + x_2 + \cdots + x_n}{n}. \tag{1}$$

Sample standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n-1}}. \tag{2}$$

Coefficient of variation:

$$\delta = \frac{\sigma}{\overline{x}}. \tag{3}$$
Terzaghi et al. discovered that the macro and micro physical and mechanical properties of rock and soil are often inseparable and interact with each other; thus, the soil mechanical properties can be regarded as the external macro performance of changes in various physical and mechanical indexes\(^{[23]}\). The correlation coefficient, \(R\) (or the coefficient of determination \(r^2\)), describes the degree of interaction and correlation between different physical and mechanical properties of rock and soil. A linear relationship is observed to be optimal for describing the relationship between each index after comparing various relationship models. Therefore, this study calculated the physical and mechanical indexes of soft clay in each statistical area using the linear regression analysis method and obtained their correlation and distribution characteristics. The correlation coefficient between the regression parameters was calculated using Eq. (4):

\[
R = \frac{\sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} = \sqrt{r^2}.
\]

Based on the aforementioned calculation principle, the primary physical and mechanical indexes of soft clay in the studied area were statistically analyzed.

4 Physical and mechanical properties and their correlation

4.1 Physical indexes

The correlation between laboratory and field test results and the structural characteristics of the soil in terms of aspects such as gradation, water content and density, void ratio, specific gravity, liquid plastic limit, permeability, and compression, was established using statistics of typical physical indexes of soft clay collected in China.

4.1.1 Physical index statistics

Analysis of the statistical calculation results listed in Table 1 and illustrated in Figures 2–13 reveals the following.

1) Although each statistical area’s sedimentary environment and soft clay origin are distinct, several physical property indexes reveal certain similarities. The variability of physical indicators such as density, specific gravity, plastic limit, and liquid limit is minimal. The coefficient of density variation is the least among them, and the overall distribution range is relatively concentrated. The minimum value is found in fluvial or lacustrine sedimentary soft clay or urban dredging soft clay, whereas the maximum value is mostly found in marine sediment soft clay. The narrow variation range of these physical indexes, excluding certain outliers, is the reason for the low coefficient of variation, which reflects the weak regional characteristics of some physical properties of soft clay.

2) Water content, void ratio, plasticity index, liquid index, permeability, and compressibility of the soft clay in the different statistical areas exhibit marked variability, with the coefficient of variation of permeability, \(k_v\), being largest, reaching a value of 1.00 due to the influence of the sedimentary environment and sampling depth. The soft clay hardness is mainly affected by water content and void ratio. Thus, the coefficient of variation of the liquidity index is also large compared with other physical indicators. Most soft clay has undergone several physical and chemical changes due to self-weight compaction, compression, and groundwater-level fluctuation, and these factors have different effects on the soil’s physical properties that reflect obvious regional and discrete variations.

3) The aforementioned physical property indicators should be regarded as secondary factors when undertaking foundation design and reliability calculations\(^{[24]}\).
4.1.2 Correlation analysis

Correlation analysis was performed on the soft clay physical properties in each statistical area and an empirical formula was fitted (Table 2). Figures 14–21 illustrate the statistical relationship of each mechanical index.

### Table 1. Results of statistical analysis of physical indexes of soft clay

| Test characteristic value | Number of test groups | Minimum value (Location) | Maximum value (Location) | Average value | Standard deviation | Coefficient of variation |
|---------------------------|-----------------------|--------------------------|--------------------------|---------------|--------------------|--------------------------|
| Water content (%)         | 311                   | 20.30 (Qingyi River)     | 180.00 (Daya Bay, Huizhou)| 47.81         | 27.49              | 0.58                     |
| Density (g/cm³)           | 283                   | 1.18 (Qinhuai River)     | 2.00 (Qingyi River)      | 1.79          | 0.18               | 0.10                     |
| Void ratio                | 290                   | 0.64 (Qingyi River)      | 5.93                     | 1.27          | 0.68               | 0.53                     |
| Specific gravity          | 152                   | 2.60 (Qinhuai River)     | 2.74                     | 2.71          | 0.14               | 0.06                     |
| Liquid limit (%)          | 125                   | 10.90 (Hefei, Anhui)    | 75.00 (Wulihu, Wuxi)     | 42.95         | 10.98              | 0.26                     |
| Plastic limit (%)         | 125                   | 0.87 (Hefei, Anhui)      | 35.3 (Kunming Yunxin Hotel)| 23.69        | 4.23               | 0.18                     |
| Plasticity index          | 100                   | 10.1 (Qingyi River)      | 48.3 (Zhanjiang breakwater)| 18.67        | 7.60               | 0.41                     |
| Liquidity index           | 121                   | 0.10 (Qingyi River)      | 8.56                     | 1.58          | 1.54               | 0.97                     |
| Permeability coefficient $k_v$ (10⁻⁷ cm/s) | 29 | 0.33 (Qingyi River) | 11.00 (Luchao port, Shanghai) | 0.87 | 0.46 | 1.00 |
| Permeability coefficient $k_h$ (10⁻⁷ cm/s) | 12 | 1.38 (Guangzhou) | 13.2 (Quanzhou Bay, Fujian) | 5.09 | 3.11 | 0.61 |
| Compressibility (MPa⁻¹)   | 105                   | 0.109 (Yuecheng Reservoir) | 2.76 (Sanshan, Zhejiang) | 0.90          | 0.59               | 0.66                     |
| Compression modulus (MPa) | 0.6  | 11.77 |
|---------------------------|------|-------|
| (Bali Lake, Jiujiang)     | 97   | 3.16  |
| (Kunming tofu camp)       |      | 2.00  |
|                           |      | 0.63  |

- **Figure 2.** Distribution histogram of water content
- **Figure 3.** Distribution histogram of density
- **Figure 4.** Distribution histogram of void ratio
- **Figure 5.** Distribution histogram of specific gravity
- **Figure 6.** Distribution histogram of liquid limit
- **Figure 7.** Distribution histogram of plastic limit
Figures 14–21 and Table 2 show that the soft clay physical indexes in each statistical area reflect certain correlations. The linear correlation between the liquid limit and plasticity index is strongest (R > 0.93), indicating that the soft clay liquid limit and plasticity index in various areas increase synchronously. In addition, the water content, void ratio, density, and compressibility also exhibit an appreciable correlation. The higher the water content of the different soft clays, the greater the void ratio, the lower the natural density, and the greater the compressibility. However, the linear correlation between the permeability coefficient, density, and water content is rather weak, which may be related to the different pore development and measured water head differences of the soft clay in different sedimentary environments. Air bubbles that could block drainage channels and further reduce permeability are generated when the organic matter content is large. Therefore, the soft clay permeability coefficient should be the focus of actual in situ measurement.

4.2 Mechanical properties
The soft clay strength characteristics significantly influence dam operating safety and maintenance. The methods widely used to test the soft clay strength include the vane shear test, triaxial compression test, direct shear test, and unconfined test. This section compares and analyzes the soft clay mechanical properties determined using different test methods. Notably, the test results are closely related to the loading rate and consolidation conditions.
Figure 14. Statistics of the relationship between water content and density

Figure 15. Statistics of the relationship between void ratio and density

Figure 16. Statistics of the relationship between liquid limit and plasticity index

Figure 17. Statistics of the relationship between vertical permeability coefficient and density

Figure 18. Statistics of the relationship between vertical permeability coefficient and water content

Figure 19. Statistics of the relationship between water content and compressibility
Figure 20. Statistics of the relationship between void ratio and compressibility

Figure 21. Statistics of the relationship between density and compressibility

| Test soil sample | Correlation index | Linear regression equation | Correlation coefficient | Determination coefficient |
|------------------|-------------------|-----------------------------|------------------------|--------------------------|
|                  | \( \omega \sim \rho \) | \( \omega = -113.6600\rho + 249.7200 \) | 0.8150 | 0.6642 |
|                  | \( e \sim \rho \) | \( e = -3.4812\rho + 7.5064 \) | 0.8677 | 0.7529 |
|                  | \( W_L \sim I_p \) | \( W_L = 0.8424I_p - 16.6670 \) | 0.9386 | 0.8810 |
| Soft clay        | \( k_v \sim \rho \) | \( k_v = -4.0640\omega + 8.4324 \) | 0.6198 | 0.3841 |
|                  | \( k_v \sim \omega \) | \( k_v = -0.0200\omega + 1.0431 \) | 0.1449 | 0.0210 |
|                  | \( \omega \sim a_v \) | \( a_v = 26.0450\omega + 23.9520 \) | 0.8415 | 0.7081 |
|                  | \( e \sim a_v \) | \( a_v = 0.6686e + 0.6989 \) | 0.7877 | 0.6205 |
|                  | \( \rho \sim a_v \) | \( a_v = -0.1962\rho + 1.9214 \) | 0.6610 | 0.4369 |

### 4.2.1 Statistics of mechanical indexes

Analysis of the statistical calculation results listed in Table 3 and illustrated in Figures 22–30 reveals the following.

1. The mechanical strength index of soft clay in each statistical area is low due to the high natural water content and large void ratio. The minimum values of mechanical indexes are mostly found in marine sediment, unlike the physical indexes, whereas the strength characteristics of fluvial and lacustrine sediments are relatively high.

2. The variation coefficients of the mechanical indexes of soft clay are large, which is consistent with previous research results\(^{[25]}\). The soft clay mechanical indexes are more dispersed and have a broader range of variation than the physical indexes, indicating that soft clay mechanical properties are more discrete and random, even if the physical properties of the soft clay in the same area are similar. However, because soft clay has a loose structure, there is difficulty with particle arrangement and combination, which could lead to differences in its mechanical properties.

3. To improve the reliability of foundation design in engineering applications, the soil’s mechanical properties must be regarded as random variables and the influence of the variation coefficient must be considered\(^{[22]}\). Large calculation errors could result if the mechanical properties of the soil are regarded as constants.

Table 3. Mechanical indexes of soft clay in each statistical area
| Test characteristic value | Number of test groups | Minimum value (Location) | Maximum value (Location) | Average value | Standard deviation | Coefficient of variation |
|---------------------------|-----------------------|--------------------------|--------------------------|---------------|--------------------|--------------------------|
| Vane shear strength (kPa) | 15                    | 2.0                      | 26.38                    | 13.68         | 6.51               | 0.48                     |
|                           |                       | (Huangdao, Qingdao)      | (Zhoushan, Zhejiang)     |               |                    |                          |
| Internal friction angle (UU, °) | 13               | 1.2                      | 12.5                     | 7.15          | 3.26               | 0.46                     |
|                           |                       | (Jiaomen, Guangzhou)     | (Qingyi River)           |               |                    |                          |
| Cohesion (UU, kPa)       | 13                    | 4.5                      | 29.0                     | 20.45         | 7.99               | 0.39                     |
|                           |                       | (Jiaomen, Guangzhou)     | (Qingyi River)           |               |                    |                          |
| Internal friction angle (CU, °) | 40              | 3.9                      | 22.0                     | 13            | 4.43               | 0.34                     |
|                           |                       | (Lianyungang)             | (Qingyi River)           |               |                    |                          |
| Cohesion (CU, kPa)       | 40                    | 1.7                      | 38.2                     | 15.14         | 6.9                | 0.46                     |
|                           |                       | (Bali Lake, Jiangxi)      | (East Lacustrine, Wuhan)  |               |                    |                          |
| Internal friction angle (CD, °) | 5                | 5.0                      | 17.9                     | 9.92          | 4.15               | 0.42                     |
|                           |                       | (Bali Lake, Jiangxi)      | (Yuecheng Reservoir)     |               |                    |                          |
| Cohesion (CD, kPa)       | 5                     | 8.6                      | 27.0                     | 13.18         | 7.01               | 0.53                     |
|                           |                       | (Lianyungang)             | (Bali Lake, Jiangxi)     |               |                    |                          |
| UCS (kPa)                | 5                     | 10.84                    | 52.4                     | 25.1          | 14.5               | 0.58                     |
|                           |                       | (Quanzhou Bay, Fujian)    | (Lianyungang)            |               |                    |                          |

**Figure 22.** Distribution histogram of vane shear strength (UU)

**Figure 23.** Distribution histogram of cohesion
Figure 24. Distribution histogram of internal friction angle (UU)

Figure 25. Distribution histogram of cohesion (CU)

Figure 26. Distribution histogram of cohesion (CD)

Figure 27. Distribution histogram of internal friction angle (CD)

Figure 28. Distribution histogram of cohesion in a direct shear test

Figure 29. Distribution histogram of internal friction angle in a direct shear test
4.2.2 Correlation analysis

Correlation analysis was performed on the mechanical properties of the soft clay in each statistical area and the empirical formula was fitted (Table 4). Figures 31–48 illustrate the statistical relationship of each mechanical index.

A certain correlation exists between the mechanical indexes of the soft clay in each statistical area. The correlation coefficients are mostly >0.55, but these values are lower than those derived for the physical indexes. Table 4 shows that the mechanical indexes of soft clay exhibit the strongest linear correlation with natural water content, void ratio, and density. The cohesion and internal friction angle decrease as the void ratio and water content increase, but increases with the density. This is because the water content and void ratio indicate the proportions of solid material and voids in the soil. Thus, they determine the effective contact area of soil particles and the compactness of a unit area section, implying that they are closely related to the internal friction angle and cohesion of the soil.

The results of the triaxial and direct shear tests show a certain degree of correlation between strength and plasticity index. The plasticity index is related to the soil’s bound water content. The greater the thickness of the bound water film, the higher the plasticity index. Further, the higher the plasticity index, the smaller the internal friction angle due to the lubrication effect of water in the soil’s shearing process.

The water content, density, and plasticity index of the soil samples in different regions significantly impact the internal friction angle (φ) of the direct shear test. Further, the inhomogeneity of point distributions in the statistical relationship illustrates that the difference between the soil properties in the different regions is due to the sedimentary environment and the buried depth.
Figure 33. Statistics of the relationship between water content and vane shear strength

Figure 34. Statistics of the relationship between plasticity index and vane shear strength

Figure 35. Statistics of the relationship between cohesion and void ratio (UU)

Figure 36. Statistics of the relationship between cohesion and density (UU)

Figure 37. Statistics of the relationship between cohesion and water content (UU)

Figure 38. Statistics of the relationship between internal friction angle and void ratio (UU)
Figure 39. Statistics of the relationship between internal friction angle and density (UU)

Figure 40. Statistics of the relationship between internal friction angle and water content (UU)

Figure 41. Statistics of the relationship between cohesion and void ratio (CU)

Figure 42. Statistics of the relationship between cohesion and water content (CU)

Figure 43. Statistics of the relationship between cohesion and density in direct shear test

Figure 44. Statistics of the relationship between cohesion and water content in direct shear test
Table 4. Results of correlation analysis between mechanical indexes and physical indexes

| Test soil sample | Correlation index | Linear regression equation | Correlation coefficient | Determination coefficient |
|------------------|-------------------|---------------------------|-------------------------|--------------------------|
| Vane shear test  | $C_u \sim \epsilon$ | $C_u = -0.6638e + 2.5304$ | 0.6125                  | 0.3075                   |
|                  | $C_u \sim \rho$   | $C_u = 0.104\rho + 1.5374$ | 0.5407                  | 0.2924                   |
|                  | $C_u \sim \omega$ | $C_u = -2.0082\omega + 85.7180$ | 0.6228                  | 0.3879                   |
|                  | $C_u \sim I_p$    | $C_u = 0.9011I_p + 7.3281$ | 0.6748                  | 0.4554                   |
| Triaxial compression test (UU) | $c \sim \epsilon$ | $c = -0.043e + 1.9157$ | 0.8748                  | 0.7652                   |
|                  | $c \sim \rho$    | $c = 0.0162\rho + 1.5334$ | 0.9186                  | 0.8438                   |
|                  | $c \sim \omega$  | $c = -1.6126\omega + 70.7070$ | 0.8784                  | 0.7716                   |
| Equation | Coefficient | R²       | P-value |
|----------|-------------|----------|---------|
| $\varphi \sim e$ | $\varphi = -0.1065e + 1.7963$ | 0.8823 | 0.7785 |
| $\varphi \sim \rho$ | $\varphi = 0.0390\rho + 1.5858$ | 0.9024 | 0.8143 |
| $\varphi \sim \omega$ | $\varphi = -4.0041\omega + 66.3370$ | 0.8892 | 0.7907 |
| $c \sim e$ | $c = -0.0300e + 1.7055$ | 0.6678 | 0.4460 |
| $c \sim \omega$ | $c = -1.1353\omega + 62.4130$ | 0.6486 | 0.4207 |
| $c \sim \rho$ | $c = 0.0080\rho + 1.6467$ | 0.6103 | 0.3725 |
| $c \sim \omega$ | $c = -0.7684\omega + 56.4590$ | 0.5538 | 0.3067 |
| $c \sim I_p$ | $c = -0.1881I_p + 19.0850$ | 0.4259 | 0.1814 |
| $\varphi \sim \rho$ | $\varphi = 0.0073\rho + 1.7443$ | 0.2561 | 0.0656 |
| $\varphi \sim \omega$ | $\varphi = -0.9511\omega + 50.7220$ | 0.3362 | 0.1130 |
| $\varphi \sim I_p$ | $\varphi = -0.2123I_p + 18.2820$ | 0.3140 | 0.0986 |

5 Conclusions

1. Physical indexes such as density, specific gravity, plastic limit, and liquid limit in China’s soft clay exhibit a relatively small variability, whereas water content, void ratio, plasticity index, liquid index, permeability, and compressibility show greater variability. The minimum (maximum) values are observed in fluvial and lacustrine sediments, and urban dredged sediments (marine sediments).

2. The variation coefficient of the mechanical indexes is larger than the physical indexes, and the mechanical indexes' minimum values are mostly observed in marine sediments, whereas the strength characteristics of fluvial and lacustrine sediments are relatively high.

3. The soft clay physical indicators in each statistical area, except the permeability coefficient, reflect a reasonably strong correlation. Further, there is a high degree of correlation between the regression equations of the mechanical and physical indexes such as moisture content, density, void ratio, and plasticity index. However, the water content, density, and plasticity index of samples in different regions have a greater impact on the $\varphi$ value of the direct shear test.

4. Physical indexes with strong correlations can be estimated using linear regression equations in geotechnical tests and engineering construction applications to avoid repetitive labor. Mechanical indexes with weak correlations should be regarded as independent random variables to minimize errors in engineering applications.

5. The results of this study have a certain universal value and provide a foundation for interregional and multidirectional treatment of soft clay and the promotion of soft clay embankment engineering.

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