Study on the engineering characteristics and microstructures of different types of soft clay

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Abstract. Basic research on the physical properties of soft clay currently lags behind the construction of buildings and infrastructure, such as dams, on these soils. To address this issue, the present study analyzed the engineering physical characteristics, mineral composition, and microstructure of three sedimentary types of soft clay, namely, fluvial deposits, lacustrine deposits, and marine deposits. Soft clays of different sedimentary types were mainly composed of fine silt, which accounted for approximately 80% of their composition, and characterized by generally high water contents. The maximum amount of lacustrine deposits in the soft clay was 186.0%. Other engineering properties showed certain levels of discreteness and variability. X-ray diffraction analyses revealed that the different sedimentary soft clays were mainly composed of similar minerals with varied relative proportions. Moreover, because many of the clay minerals identified showed strong hydrophilicity, the combined water quantity of the sedimentary soft clay was the key factor influencing its engineering stability. The soft clays were mainly composed of laminated clots and flocs. Compared with those of fluvial and marine deposits, the pore shape of lacustrine sedimentary soft clay was more complex, and the pore connectivity of the latter was poorer. This study provides a reference for the engineering applications of soft clay.

Keywords: Engineering characteristics, Microstructures, Soft clay

1. Introduction

The application of soft clay in dam engineering presents many hidden dangers because this substrate is restricted by its characteristics of high water content, low permeability coefficient, and long consolidation deformation time. During their construction and operation, many projects on soft clay are associated with a high risk of damage or degeneration, which can lead to major social impacts and economic losses; this limitation seriously restricts the applications of soft clay in engineering construction[1-3]. Moreover, because some sediments cannot be directly applied to the filling of dams and road projects, they are often discarded, resulting in serious resource wastage and environmental hazards[4,5].

Soft clay, a geological product generated by changes in geography, climate, and the sedimentary environment over millions of years under long-term geological actions, is mainly composed of soft clay sediments and a small amount of humus[6]. Because this type of soil mass is widely distributed worldwide, obtaining a comprehensive understanding of its engineering characteristics is necessary so that engineers can implement practical treatment measures to reduce or eliminate the negative effects of soft clay soil on engineering construction projects.

Soft clay can be divided into 22 types according to the deposition-accumulation environment, including marine soft clay, lacustrine soft clay, and fluvial soft clay. Several academics have studied the engineering characteristics of some soft clays with unique generation characteristics[7-9], but soft clays from sedimentary environments often have a complex structure, and their formation conditions and
geological origins have an important impact on their engineering characteristics\cite{10}. Thus, the discreteness and variability of different types of soft clays must be considered to evaluate their soil parameters comprehensively and improve the accuracy of physical and mechanical parameter selection.

Mineral composition is an important factor that determines the physical and engineering properties of soft clay\cite{11} and a crucial indicator of regional soil characteristics. The mineral composition of different types of soft clay can not only reflect the latter’s sedimentary environment but also provide a reference for its use in engineering construction. Moreover, as a natural product, clay is composed of numerous soil particles of different sizes. The arrangement, shape, combination form, and mutual collocation of soil particles and pore structures directly affect the hydrophilicity and relative gas contents of the substrate. The macroscopic engineering properties of soft clay are largely controlled by the system state or overall structure of its microstructure. Moreover, the physical and mechanical properties of the soft clay represent the macroscopic reactions of its microscopic properties. The relationship between different particles in the soft clay can be directly revealed by scanning electron microscopy (SEM)\cite{12}. While previous studies mostly focused on the microscopic characteristics of a specific type of soft clay\cite{13-15}, comparative analyses of the mineral compositions and microstructures of soft clay soils of different sedimentary types are scarce.

The present study summarizes and analyzes the physicomechanical properties, mineral compositions, and microstructures of three different sedimentary types of soft clay found in relying projects, including marine facies, lake facies, and rivers. The results of this analysis will lay a strong foundation for the cross-regional and multi-directional treatment and resource utilization of soft clay, as well as the popularization and utilization of soft clay dam projects.

2. Test materials

Soft clay has a complex genesis process and wide distribution. Therefore, the geographical, genetic, engineering, and economic factors of soft clay must be comprehensively studied to determine its engineering applications. In this study, the results of engineering investigations were combined with the specific characteristics of typical soft-clay dam projects, including the Qingyi River spillway project in Wuhu, Anhui Province, China, the Qilu Lake patrol road project in Yuxi, Yunnan Province, China, and the alkali residue field project of Tangshan Sanyou Chemical Co., Ltd. in Hebei Province, China. The engineering physical and structural characteristics of fluvial soft clay, lacustrine soft clay, and marine soft clay were then studied.

3. Engineering physical properties

The engineering physical index of soft clay directly reflects of its engineering characteristics. While their parameters are often interrelated, the engineering physical characteristics of different soft clays are often discrete and variable. Thus work analyzed the engineering characteristics of five physical indices as follows.

3.1 Particle gradation

The particle size distribution refers to the relative proportion of each particle size class in the soil. The proportion of each particle size range in each particle group is one of the factors determining the properties of soft soil and closely related to the soil engineering characteristics. In general, soft clay contains a large number of fine soil components, including soft clay and clay.
Figure 1. Comparison of the particle size curves of the three sedimentary types of soft clay in the different dam projects

The particle size distribution curves of the three soft clay sedimentary types at different locations encountered in the dam projects described earlier were showed in Figure 1. Although the sedimentary types differed, the particle size distributions of the clays were similar, and no clear zonal distribution could be observed in the curves. Most of the soft clay particles were distributed between 0.001 and 0.1 mm, with a maximum size of 1.0 mm. The particle size of the clay was generally small, and the clay generally behaved as a powder in dry conditions and was malleable under wet conditions.

Table 1. Statistics of the soft clay fractions of different sedimentary types

| Project location          | Sedimentary type | Grain fraction content (%) |
|---------------------------|------------------|----------------------------|
|                           |                  | Sand group >0.075 mm | Farinograph 0.005–0.075 mm | Clay group <0.005 mm |
| Yuxi City, Yunnan Province| Lacustrine deposits | 14                  | 77                       | 9                        |
| Tangshan City, Hebei Province| Marine deposits   | 1                   | 91                       | 8                        |
| Qingyi River, Anhui Province | Fluvial deposits  | 1.5                 | 65.5                     | 33                       |

Table 1 showed the statistical results of the contents of the particle groups of different soft clay sedimentary types.

The soft clay particles mainly measured <0.075 mm in size, and the mass of particles larger than 0.1 mm was less than 20% of the total mass of the sample. The soft clay group accounted for approximately 80% of the clay composition, which was similar to the particle size characteristics of soft clay observed in previous studies[16, 17].
Figure 2. Comparison of the typical particle fractions curves of different sediment soft clays

The statistics of the soft clay particle fraction curve in Table 1 was further adjusted to obtain the upper inclusion line, the lower inclusion line, and the average gradation, as showed in Figure 2. The particle size distribution of soft clay particles located between the upper and lower inclusion lines was mostly concentrated between 0.001 and 0.1 mm. The average gradation showed that the sum of the mass of particles measuring <0.1 mm in size exceeded 90% of the total mass, and the content of soft clay was greater than 50%.

Given the large content of fine particles in the samples, the ability of soil particles to adsorb combined water was strong, as reflected by their physicomechanical properties of high plasticity index and low permeability coefficient and engineering properties of low consolidation speed, low strength, and large creep.

3.2 Specific gravity of the soil particles

The specific gravity of the soil particles is a major evaluation index of soil structural characteristics, and its value depends on the mineral composition of the soil. In general, the specific weight of clay soil is higher than that of sandy soil. If the soil contains organic matter and peat, its specific weight decreases. As the particle sizes of the three types of deposited soft clays were generally less than 5.00 mm, the specific gravity flask method was used for measurement, as shown in Figure 3.

Figure 3. Specific gravity test of soft clay

The specific gravity of soil particles was mainly controlled by the mineral composition of the soil. The results in Table 2 showed that the specific gravity of different sedimentary types in the dam projects was between 2.62 and 2.70. Moreover, the marine and lacustrine environments were more favorable to the deposition of fine-grained soil than the fluvial environment, and the proportion of fine-grained soft clay was higher in the former than in the latter. As such, the proportions of marine and lacustrine soft clay in the samples were slightly higher than that of the fluvial clay. However, the particle size distributions of all three soil types were within a similar range, which indicates that the proportions of these three types of soft clay soil particles were relatively similar with low variability.

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Table 2. Statistics of the specific gravity of the studied soft clays

| Sample number | Project location         | Sedimentary type       | Specific gravity |
|---------------|--------------------------|------------------------|------------------|
| 1             | Yuxi City, Yunnan Province | Lacustrine deposits    | 2.68             |
| 2             | Tangshan City, Hebei Province | Marine deposits       | 2.70             |
| 3             | Qingyi River, Anhui Province | Fluvial deposits       | 2.62             |

3.3 Natural water content

Soft clays generally have high natural water contents. Samples were collected from an undisturbed soil column with a ring knife during field drilling, sealed, and brought to the laboratory for drying until a constant weight was achieved to obtain the natural water content. The natural water contents of the studied soft clays were shown in Table 3.

Table 3. Statistics of the natural water content of the studied soft clays

| Sample number | Sedimentary type      | Sampling depth (m) | Water content (%) | Maximum water content (%) | Range | Coefficient of variation |
|---------------|-----------------------|--------------------|-------------------|--------------------------|-------|-------------------------|
| 1             | Marine deposits       | 13.8–27.0          | 20.5              | 42.5                     | 20    | 0.50                    |
| 2             | Lacustrine deposits   | 8.8–14.1           | 73.6              | 186.0                    | 112.4 | 1.80                    |
| 3             | Fluvial deposits      | 1.0–4.2            | 28.6              | 31.4                     | 2.8   | 0.70                    |

Table 3 showed that the water contents of the marine sedimentary soft clay in this study ranged from 20.5% to 42.5%. The water content of lacustrine sedimentary soft clay was between 73.6% and 186.0%, and that of fluvial sedimentary soft clay was 20.3%–40.8%. In this study, differences in the water contents of fluvial and marine sediments were small, whereas the natural water content of lacustrine sedimentary soft clay was relatively high. Thus, soft clays of different sedimentary types showed remarkable variability in water content.

Changes in water content could directly lead to changes in the mechanical properties of soft clay; specifically, the higher the water content, the lower the strength of the clay. Therefore, reducing the water content of the soft clay/soft soil foundation was necessary to achieve greater bearing capacity and stability. Previous studies showed that reinforcement of soft clay with cement could obviously improve the compressibility of the former and significantly improve the strength of the resultant material within a short period of time \[18\]. Therefore, cement should be used in construction projects on soft clay with high water contents.

3.4 Void ratio

In general, soft clay has high porosity, high compressibility, low shear strength, high viscosity, and plastic properties. After remolding, the shear strength decreases because of the destruction of the flocculent structure. Under the action of an external force, soft clay particles easily form a soft soil, which poses great challenges to pre-treatment efforts prior to engineering projects.

The porosity of soft clay depends on the size, shape, quantity, and connectivity of the pores and their relation to the solid particle properties of soft clay, as well as the size, distribution, shape, arrangement, and combination degree of large particles or aggregates. Thus, porosity plays an important role in the engineering geology and hydrogeology of soft clay.

Table 4. Statistics of the void ratio of the studied soft clays

| Sample number | Sedimentary type | Sampling depth (m) | Minimum void ratio | Maximum void ratio | Range | Coefficient of variation |
|---------------|------------------|--------------------|--------------------|--------------------|-------|-------------------------|

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Table 4 showed the porosity ratios of the studied soft clays. The pore ratio of marine sedimentary soft clay in the studied soils ranged from 0.62 to 1.18, while the pore ratio of lacustrine sedimentary soft clay ranged from 1.06 to 1.42. The porosity ratio of fluvial sedimentary soft clay was between 1.06 and 1.42. In addition, among the samples, marine sedimentary soft clay showed the greatest variability in void ratio (i.e., 0.44), whereas fluvial sedimentary soft revealed the smallest (i.e., 0.10). In general, the pore ratio showed the following order: lacustrine sediments > marine sediments > fluvial sediments. However, considering the influence of sampling depth, the thicker marine soft clay revealed the greatest dispersion; indeed, this clay type was characterized by nonuniformity, low permeability, and poor consolidation effects during practical engineering.

### 3.5 Limit water content
The water content of soft clays varies considerably and could give rise to different states, namely, solid, semi-solid, plastic, and flow. The limit water content could be used to distinguish the different states of cohesive soil. The liquid and plastic limits of the three types of soft clay were showed in Table 5.

**Table 5.** Soft clay liquid and plastic limit test results and plasticity and liquidity indices

| Sample number | Sedimentary type       | Sampling depth (m) | Liquid limit (%) | Plastic limit (%) | Plasticity index | Liquidity index |
|---------------|------------------------|--------------------|-----------------|------------------|-----------------|----------------|
| 1             | Marine deposits        | 25.5–25.7          | 24.5–46.0       | 16.0–25.7        | 8.5–20.3        | 0.40–0.64      |
| 2             | Lacustrine deposits    | 8.8–14.1           | 29.0–76.0       | 18.6–46.0        | 11–31           | 0.45–1.45      |
| 3             | Fluvial deposits       | 1.0–1.2            | 30.5–38.9       | 20.2–24.7        | 10.1–17.1       | 0.1–1.87       |

Table 5 showed that the limit water content of lacustrine sedimentary soft clay demonstrated the largest fluctuation range among the studied soils. The upper limit of the liquid and plastic limits was fairly high, thereby indicating that the soil had strong hydrophilicity. Most of the marine sediments presented hard and soft plastic states, and the soil revealed the strongest resistance to external deformation. While the limit water content of the fluvial soft clay was similar to that of the marine soft clay, the fluid index of the former fluctuated greatly, which meant the soil state had high spatial variability.

### 4. Mineral quantitative analysis
Soft clay particles are largely composed of soil minerals. These minerals can be divided according to their genesis pathways into primary minerals, such as mica, feldspar, and quartz, and secondary minerals, such as clay minerals, soluble salts, and free oxides. A clear internal relationship may be observed between the mineral and particle size compositions of soil, and the mineral composition of soil is an important factor affecting its properties. The three sedimentary soft clays were analyzed for whole rock and clay minerals by using a Rigaku TTRIII multifunctional X-ray diffractometer (Figure 4).
The crystal of each mineral has a specific X-ray diffraction (XRD) pattern, and the intensity of the characteristic peak in the XRD pattern obtained is directly proportional to the content of the mineral in the sample. The water suspension and centrifugal separation methods are used to extract particles with diameters of <10 μm and <2 μm according to the Stokes sedimentation theorem in fluid mechanics. Clay minerals with particle sizes of <10 μm were used to determine the total relative content of clay minerals in the original rock. Clay mineral samples with particle sizes of <2 μm were used to determine the relative content of various clay minerals. The XRD diffractograms of the three sedimentary soft clays were shown in Figures 5a, b, and c.

Figure 4. X-ray diffractometer used for mineral quantitative analysis

Figure 5(a). X-ray diffractogram of the fluvial sediment samples
Table 6 showed the XRD analysis results of the studied soft clay minerals. Combination of the data in the table with findings in Figures 5a, b, and c revealed that the types of non-clay minerals among different sedimentary types were relatively similar and mainly composed quartz, potash feldspar, plagioclase and dolomite, with contents of over 35%. The content of fluvial sedimentary soft clay reached 71.1%, and the marine and lacustrine sedimentary soft clays appeared to contain some calcite. Because non-clay minerals mostly existed in the form of granular and bundled crystals, their surface area was small; in this case, the higher the content of these minerals, the higher the total surface area and
density of the soil. This finding was consistent with the void ratio results described in Section 3.4.

Soft clays usually contain substantial proportions of clay mineral particles, soft clay particles, mineral crystals, and their aggregates. The shape, size, and contents of these clay particles remarkably influence the properties of the soils.

Figures 6a, b, and c showed that the clay minerals of the three types of soft clay were mainly composed of crystalline kaolinite, montmorillonite, illite, and amorphous colloids. The clay mineral content of the fluvial deposit was higher than that of the other two clay deposits because the high flow velocity of the fluvial environment is unfavorable for the deposition of fine clays; by contrast, the low flow velocity in the marine and lacustrine environments could encourage the rapid precipitation of these soft clays.

### Table 6. X-ray diffraction analysis of typical soft clay minerals

| Sedimentary type   | Qu | PF | Pl | Ca | Do | Ha | Ho | He | Gy | CM |
|--------------------|----|----|----|----|----|----|----|----|----|----|
| Marine deposits    | 22.8 | 1.9 | 5.6 | 18.9 | 5.1 | 1.9 | -  | -  | 2.0 | 41.8 |
| Lacustrine deposits| 31.1 | 1.1 | 1.0 | 14.3 | 2.1 | -  | -  | 2.4 | -  | 48.0 |
| Fluvial deposits   | 48.3 | 1.8 | 17.3 | -  | 3.7 | -  | 0.9 | -  | 1.0 | 27.4 |

*Qu, PF, Pl, Ca, Do, Ha, Ho, He, Gy, and CM referred to quartz, potassium feldspar, plagioclase, calcite, dolomite, halite, amphibole, hematite, gypsum, and clay minerals respectively.*

Because the soft clay particles were very small and have large surface energies, they were easily charged by adsorption, dissociation, or ion exchange at the interface between clay particles and aqueous solutions. These particles could attract polar water molecules and hydrated ions and, therefore, exhibit colloidal properties and strong hydrophilicity. The higher the proportion of clay particles in the sample, the smaller the particle size of the clay, the stronger its hydrophilicity, and the thicker the water film produced. The montmorillonite and smectite mixed-layer contents of marine and lacustrine soft clays were relatively high, and ion exchange could easily occur in humid environments, resulting in increases in bound water and soil instability. Thus, the amount of water bound to soft clay was an important factor influencing the consistency, plasticity, expansion, permeability, and mechanical properties of soft clay. In engineering, the replacement of high-valence cations in quicklime and fly ash was often employed as a strategy to improve the physical and mechanical properties of soft clay[19, 20].
5. Microstructural analysis

Microstructure refers to the size, shape, and surface characteristics of the structural units of soil, as well as the connection and arrangement of these structural units; it is an important factor affecting the engineering properties of soil samples. SEM is the main method used to examine the microstructure of cohesive soil. Previous studies revealed that the basic unit of soft loam presents a “granular (detritus, aggregates, aggregates), open, connected” structure, while that of soft clay presents a “flokulent (flokulent), open, long chain connected” structure[21].
The samples were completely dried by a Feiquanta 200 scanning electron microscope, sprayed with gold for 90 s, and then observed at a voltage of 15–20 kV. The minerals on the glass beads were slowly ground by an agate mortar until clear particles were no longer observed.

The Cu target (40 kV, 200 mA) of the polycrystalline diffractometer (D/max2550hb + /PC) was applied, and the sweep angles ranged from 5° to 100°. The sweep rate used for diffraction analysis was 4°/min. We compared the diffraction peaks obtained under these conditions with the standard crystal diffraction data to obtain the crystal contents of the sample. SEM and computer image processing technology were employed to obtained several scanning photos of the soil microstructures (Figures 7a, b, and c).
Figures 7a, b, and c showed that the microstructures of the three types of soft clay were mainly composed of laminated agglomerates and flocs; the agglomerates mainly included those filled between the pores of soft clay or sand particles and those formed by the agglomeration and granulation around fine clastic minerals. The inner region of the agglomerates was closely arranged and slightly inlaid into each other. The loose porous flocs were arranged in a mosaic-like pattern or open form. The structure of undisturbed soil sample mainly resembled honeycomb and flocculation structures. The contact modes of the particles in the soil sample were edge-to-edge contact, edge-to-face contact, and face-to-face contact. Among these contact modes, the first two represented the majority of the samples.

The aggregates showed isolated pores with poor connectivity; these pores had little influence on the permeability but an important influence on the compressibility of the soil. Numerous intergranular pores were present between granular and clay particle-based aggregates and showed good connectivity. These pores played an important role in the porosity, compressibility, and permeability consolidation of soft clay. Small intragranular pores were mainly present in the granular and micro aggregates; these pores demonstrated extensive dispersion and poor overall connectivity and greatly affected the compressibility of soil.

Compared with the fluvial and marine sediments, the lacustrine sediments had more complex pore shapes, poorer pore connectivity, and a higher pore ratio, which was consistent with the test results described in Section 3.4.

6. Conclusion
1. The particle sizes distributions of soft clay among the three clay types studied were similar. Fine-grained soil accounted for approximately 80% of the clay composition, and the particle size composition of the soil was mainly soft clay or clay.

2. The proportions of soil particle in the three sedimentary soft clays in this study were relatively similar; however, the limit water contents and void ratios showed clear spatial variability. The natural water content the fluvial and marine sediments was similar, and that of the lacustrine sediments was relatively high.

3. The mineral composition of the three soft clays was similar but their contents varied. The clay minerals mainly comprised crystalline kaolinite, montmorillonite, illite, and amorphous colloids with colloidal properties and strong hydrophilicity. Thus, engineering projects should consider the bound water of soft clay. The main types of non-clay minerals included quartz, plagioclase and dolomite.

4. The microstructure of different types of soft clay mainly comprised laminated conglomerates and flocs. Compared with those of fluvial and marine sediments, the pore shape of lacustrine sediments was more complex, their pore connectivity was poorer, and the pore ratio was higher.

5. This study provides a reference for reducing or eliminating the negative impact of silt on various sedimentary environments during engineering construction.
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