Geotechnical behavior of soft dredger fill and deep sea soft clay

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Abstract. A full understanding of the geotechnical properties of deep sea soil is necessary for ocean engineering construction, and the basis is the evaluation and testing of undisturbed deep sea soil. Therefore, to investigate the geotechnical properties of deep sea soil, a series of experimental tests were conducted in this study. Furthermore, the test results of the deep sea soil were compared with that of the soft dredger fill. The results showed that deep sea soil comprised of high contents of clay minerals and fine particles as well as high compressibility and low strength. Compared with soft dredger fill, the mineral composition and microscopic characteristics of deep sea soil is greatly different, which is the main reason for the differences in their geotechnical properties. This study provides great support for understanding and evaluating geotechnical properties of the deep sea soil and provides an effective method for the preparation of deep sea soil samples.

Key words. Soft dredger fill, deep sea soft clay, experimental tests, geotechnical behavior

1 Introduction

The ocean, which accounts for over 70% of the earth’s total area, is one of the most attractive spaces for human development. To explore the rich mineral resources, biological resources, and abundant energy resources in the ocean, ocean engineering around the world has rapidly developed in recent years. As the development of ocean resources has become increasingly prosperous, a large number of deep sea engineering projects have been planned and constructed, such as offshore platform foundations (Tjelta, 1986, 1995; Zhang, 2007; Villalobos, 2010; Li, 2012) and submarine pipelines (Văn, 1990; Liu, 2016; Ajdehak, 2018). Therefore, the study of deep sea soil has become an important research basis for deep sea engineering development.

The ocean is a relatively special sedimentary environment, and the fundamental properties and occurrence environment of deep sea soil are rather different from those of land deposit soil. The study of deep sea soil has been a topic of concern to scholars for quite some time. As the demand for the development of marine resources continues to grow, research on marine soil has also increasingly deepened. As regards the basic composition of marine soil, Rosenqvist (1946) and Bjerrum (1954, 1967) proved that Norwegian marine clay contained a considerable amount of true clay minerals, such as illite. Leinen and King (1983, 2008) investigated the quantitative clay mineralogy of the Northwest Pacific Pelagic Clays, and the results indicated that illite was the dominant clay mineral (39\%) with lesser amounts of chlorite (19\%) and minor amounts of kaolinite and smectite (10\%), and the results...
were consistent with the study of Heath and Pisias (1979) and Griffin (1968).

Regarding the mechanical properties of marine and deep sea soil, Silva (1976, 1979, 1984) used the GPC method to obtain deep sea soil samples in the northwestern Atlantic, and it was revealed that the shear strength of deep sea soil was quite low and actually decreased with the depth. Hamilton (1976) illustrated the porosity reduction and increased density of deep sea soil under overburdened pressure by a series of laboratory and in situ tests. Velde (1996) analyzed the compaction trends of the clay-rich deep sea soil and revealed that the initial porosity of the clay-rich deep sea soil sharply decreased with increasing depth. Taylor and Leonard (1990) proved that deep sea soil was almost exclusively underconsolidated and showed a greater degree of underconsolidation with depth below the seafloor. Wang (2013) investigated the development of strain and pore-water pressure of soft marine clay with a series of high cyclic triaxial tests and revealed that the resilient strain was nearly stable after 1000 cycles, and the permanent strain slowly increased with increasing cyclic stress ratio (CSR). Lei and Xu (2020) studied the deformation and microscopic characteristics of marine soft clay under cyclic loading and presented that a low CSR induced stable deformation, while high CSR caused increased deformation, which led to the destruction of the soil structure. Huang and Wen (2020) discussed the effects of pore-water pressure on the geotechnical characteristics of marine soft soil, and the results showed that excess pore-water pressure weakened the unloading strength of the marine soft soil. In terms of the microstructure of marine and deep sea soil, Luo (1989) proved that deep sea soil had a complex and variable microstructure, and the clay minerals in the soil were mainly flaky aggregates and flocs, while the detrital minerals primarily experienced a granular stacking structure. Kong and Lv (2001) analyzed the microstructure of Zhanjiang deep sea soil by scanning electron microscopy and mercury intrusion porosimetry tests and demonstrated that there were a large number of flaky and granular particles in the soil, and the pore structure in this soil was primarily medium and small pores. Moreover, there were basically no pores larger than 10 μm. Lee and Kim (2016) observed that there were a large number of unbroken or broken microfossils with flocculated clay minerals in the deep sea soil, and pyrite was presented in the forms of frambooids and individual euhedral crystals in this soil. Guo and Nian (2019) investigated the microscopic characteristics of deep sea soil and found that there were obvious marine life debris in the sample, and the porosity of the sample was high, while the large-diameter soil particles were wrapped by flaky clay particles, showing a loose, granular structure.

In summary, deep sea soil is a kind of material with complex deposition conditions and special occurrence environments; therefore, research on the fundamental properties of deep sea soil is an important issue in deep sea engineering safety. However, due to the difficulty in sampling deep sea soil, the test cost is relatively high and restricts the research progress on deep sea soil. Hence, it is vital to search for alternative materials for deep sea soils and perform experimental research on deep sea soil in a scientific and economical way.

In this study, the fundamental properties of deep sea soft clay were studied and compared with that of soft dredger fill. This paper analyzes the differences between the fundamental properties of the two soils from the perspectives of mineral composition, particle size composition, physical properties, and mechanical characteristics. Research results provide an important theoretical basis for revealing the fundamental properties and searching for an alternative material for deep sea soil.

2 Soil samples and fundamental properties
The soft dredger fill used in this study was taken from the Binhai District, Tianjin, China, while the deep sea soft clay was taken from the South China Sea. A series of laboratory tests were conducted to understand the fundamental physical properties of the soil samples, and the results are shown in Table 1. According to the Unified Soil Classification System (USCS), the soft dredger fill and deep sea soft clay were both classified as inorganic clays of high plasticity (CH).

| Table 1. Basic physical properties of the soft dredger fill and deep sea soft clay |
|-------------------------------|----------------|----------------|
| Index parameter               | Soft dredger fill | Deep sea soft clay |
| Water content (%)             | 89.5            | 96.7            |
| Specific gravity              | 2.73            | 2.71            |
The particle size distribution of the soft dredger fill and deep sea soft clay were measured by an NKT5200-H laser particle sizing system, and the granulometric curves are shown in Fig. 1, while the indexes of particle grading are shown in Table 2. The particle size distribution of soft dredger fill is similar to that of deep sea soft clay, while the silt content of deep sea soft clay is higher. The uniformity coefficient $C_u$ of soft dredger fill is 6.85, which means it is nonuniform soil, whereas the deep sea soft clay is uniform soil, where the uniformity coefficient $C_u$ is 4.96.

### Table 2. Indexes of particle grading of the soft dredger fill and deep sea soft clay

| Indexes                         | Soft dredger fill | Deep sea soft clay |
|---------------------------------|-------------------|--------------------|
| Effective grain size $d_{10}$ (μm) | 2.84              | 3.23               |
| Average grain size $d_{50}$ (μm)   | 13.98             | 15.25              |
| Constrained grain size $d_{60}$ (μm) | 19.44             | 16.03              |
| Uniformity coefficient $C_u$                 | 6.85              | 4.96               |
| Content of particles less than 5 μm (%)    | 20.60             | 18.75              |
| Content of particles less than 75 μm (%)   | 86.62             | 99.64              |

Additionally, X-ray diffraction (XRD) tests were conducted to determine the mineral composition of the soil samples. These tests were performed utilizing a D8 Discover diffractometer with a Cu-Kα X-ray tube, which was manufactured by Bruker Corp. A current of 200 mA and an input voltage of 40 kV were adopted. The specimens were scanned in the range from 10° to 60° for the 2 theta values, with a step length of 0.02°, a scanning rate of 2°/min, and a slit width of 0.3 mm. Ultimately, the XRD data was analyzed using JADE 5.0, Materials Data, Inc. (Yi et al., 2015). The specific mineral composition is shown in Table 3, and it can be observed that the clay minerals constitute a large proportion of the soil samples, especially soft dredger fill, which contains 50.17% clay mineral composition, while the deep sea soft clay contains 26.9% clay mineral composition.

### Table 3. Mineral composition of the soft dredger fill and deep sea soft clay

| Component (%) | Soft dredger fill | Deep sea soft clay |
|---------------|-------------------|--------------------|
| Clay          | 50.17             | 26.9               |
| Minerals       | Content (%) | Minerals       | Content (%) |
|---------------|-------------|---------------|-------------|
| Quartz        | 19.53       | Quartz        | 29.1        |
| Calcite       | 16.60       | Calcite       | 15.8        |
| Potash Feldspar| 2.50        | Potash Feldspar| 1.9        |
| Halite        | 1.63        | Halite        | 4.0         |
| Pyrite        | 0.70        | Pyrite        | 3.1         |
| Plagioclase   | 7.27        | Albite        | 13.7        |
| Dolomite      | 1.30        | Mica          | 5.5         |
| Hornblende    | 0.30        | Clay minerals | 26.9        |
| Clay minerals | 50.17       |               |             |

3 Experimental program
In this study, one-dimensional (1D) compression tests and consolidated undrained triaxial shear tests were performed to investigate the geotechnical behavior of soft dredger fill and deep sea soft clay. For the 1D compression test, soil samples were placed in the odometer cell, and two porous stones were placed on its upper and lower sides; moreover, the compression pressure increments were 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, and 1600 kPa, respectively. For the consolidated undrained triaxial shear test, a strain-controlled method was conducted with a 0.5 mm/min axial shear rate; in addition, the confining pressures of 100 kPa, 200 kPa, and 300 kPa were used, respectively, and finally, the test was stopped when the axial strain reached 15%.

4 Compression behavior
The results of the compression tests are shown in Fig. 2, which reflects the deformation development of the soil samples. It is shown that the deformation of the soil samples increases with rising compression pressure, and the difference between the deformation of the curves of soft dredger fill and deep sea soft clay becomes more notable. As shown in Fig. 2, a more significant difference in the deformation of the soil samples occurs at higher pressure. Compared with soft dredger fill, the deformation of the deep sea soft clay is 8.585 mm, which has an increase of 20.64%. This is due to the fact that the deep sea soft clay has a more uniform particle size distribution, thereby making it more compressible.

![Fig. 2 Compression deformation curves of the soft dredger fill and deep sea soft clay](image)

Moreover, $e$-$log p$ curves based on a 1D compression test are shown in Fig. 3, which reflect the...
The compressibilities of the soil samples. As presented in Fig. 3, the compression curves of the samples can be divided into two stages: (1) under a low compression pressure (< 12.5 kPa or 25 kPa), the void ratio decreased slowly, and the compression curve approximated a horizontal trend; (2) as the compression pressure gradually increased, the void ratio decreased rapidly, and the compression curve decreased in a linear fashion. In the initial stage (compression pressure < 12.5 kPa), the soft dredger fill had a lower void ratio than the deep sea soft clay. However, the void ratio of deep sea soft clay rapidly decreased with increasing compression pressure. In the later stages, the void ratio of deep sea soft clay is always lower than that of the soft dredger fill, and the void ratio difference between the two soil samples is typically around 0.1.

![Graph showing compression curves for soft dredger fill and deep sea soft clay](image)

**Fig. 3** The e-lgp curves of the soft dredger fill and deep sea soft clay

Four essential compression parameters were calculated to evaluate the compressibility of the soil samples, and the results are shown in Table 4. The coefficient of compressibility $a_{1-2}$, compression index $C_{c,1-2}$, modulus of compressibility $E_{s,1-2}$, and coefficient of volume compressibility $m_{v,1-2}$ were calculated using the following equations:

$$a_{1-2} = \frac{e_1 - e_2}{p_2 - p_1}$$  \hspace{1cm} \text{Eq. (1)}

$$C_{c,1-2} = \frac{e_1 - e_2}{\log p_2 - \log p_1}$$  \hspace{1cm} \text{Eq. (2)}

$$E_{s,1-2} = \frac{1 + e_1}{a}$$  \hspace{1cm} \text{Eq. (3)}

$$m_{v,1-2} = \frac{1}{E_{s,1-2}} = \frac{a}{1 + e_1}$$  \hspace{1cm} \text{Eq. (4)}

where $p_1 = 100$ kPa and $p_2 = 200$ kPa, and $e_1$ and $e_2$ are the void ratios of the soil samples under compression pressures $p_1$ and $p_2$, respectively.

According to the results presented in Table 4, both soft dredger fill and deep sea soft clay have a coefficient of compressibility $a_{1-2}$ greater than 0.5, which means that both types of soil show high compressibility. The coefficient of compressibility $a_{1-2}$ of deep sea soft clay is approximately 1.29 MPa$^{-1}$, which is approximately 5.13% higher than that of soft dredger fill. The compression indexes
of soft dredger fill and deep sea soft clay are 0.42 and 0.45, respectively, which is consistent with the law of e-lg curve. The modulus of compressibility \( E_{c,1-2} \) of deep sea soft clay is about 1.80, which is approximately 1.62% lower than that of soft dredger fill.

### Table 4. Compression parameters of soft dredger fill and deep sea soft clay

| Compression parameters                  | Soft dredger fill | Deep sea soft clay |
|----------------------------------------|-------------------|--------------------|
| Coefficient of compressibility \( a_{1-2} \) (MPa\(^{-1}\)) | 1.23              | 1.29               |
| Compression index \( C_{c,1-2} \)     | 0.42              | 0.45               |
| Modulus of compressibility \( E_{c,1-2} \) (MPa) | 1.83              | 1.80               |
| Coefficient of volume compressibility \( m_{v,1-2} \) (MPa\(^{-1}\)) | 0.55              | 0.56               |

### Table 5. Coefficient of compressibility of deep sea soft clay and soft soil in other regions

| Soil types                                | Coefficient of compressibility \( a_{1-2} \) (MPa\(^{-1}\)) |
|-------------------------------------------|-----------------------------------------------------------|
| Deep sea soft clay (this study)           | 1.29                                                      |
| Guangzhou Nansha soft soil (Chen et al., 2008) | 0.83                                                      |
| Wenzhou marine soft soil (Han et al., 2016) | 0.96                                                      |
| Shanghai soft clay (Song et al., 2018)    | 0.90                                                      |
| Nanjing soft clay (Zeng et al., 2012)     | 1.03                                                      |
| Lianyungang soft clay (Zeng et al., 2012) | 2.15                                                      |

Furthermore, Table 5 shows the coefficient of compressibility \( a_{1-2} \) of the deep sea soft clay and typical soft soils in other regions. It can be observed that, with the exception of Lianyungang soft clay, the coefficient of compressibility \( a_{1-2} \) of deep sea soft clay is significantly greater than that of typical soft soils in other regions. It further indicates that the deep sea soft clay is a high compressibility soil.

![Fig. 4 Coefficients of compressibility under different compression pressures](image)

To further reveal the compression behavior of the soft dredger fill and deep sea soft clay, the coefficient of compressibility under different pressures was calculated and shown in Fig. 4. It can be observed that with a compression pressure of 25 kPa as the critical point, the compressibility of soft dredger fill first increased and then decreased as the compression pressure increased; this shows that when the compression pressure gradually increases, the soil particles are rearranged due to the destruction of the soil structure, and then the soil is continuously compacted, resulting in decreased
compressibility. However, the coefficient of compressibility of deep sea soft clay continues to decrease with increasing compression pressure, and the compressibility continues to decrease.

![Graph showing ln(1+e) vs. lgp for Soft dredger fill and Deep sea soft clay](image)

**Fig. 5** Structural yield stress determined by Butterfield's ln(1+e)-lgp method

Furthermore, the structural yield stress was determined by Butterfield’s ln(1+e)-lgp double logarithmic coordinate method and shown in Fig. 5. It can be observed that the structural yield stress of soft dredger fill is significantly greater than that of deep sea soft clay, indicating that there are more significant skeletal characteristics in soft dredger fill, which further proves the previous discussion.

5 Stress-strain behavior

The stress-strain behavior of soft dredger fill and deep sea soft clay under 100 kPa confining pressure is shown in Fig. 6, which demonstrates a typical strain-hardening development: as the axial strain increases, the deviator stress (σ1-σ3) rapidly increases at first and then slowly until the sample fails. In addition, as presented in Table 6, the failure strength and elastic modulus of the deep sea soft clay were both slightly higher than that of the soft dredger fill.

![Graph showing Stress-strain relationship curves of soft dredger fill and deep sea soft clay](image)

**Fig. 6** Stress-strain relationship curves of soft dredger fill and deep sea soft clay
Table 6. Strength parameters of the soft dredger fill and deep sea soft clay

| Strength parameters | Soft dredger fill | Deep sea soft clay |
|---------------------|-------------------|--------------------|
| Failure strength (kPa) | 87.9              | 93.7               |
| Elastic modulus (MPa)   | 76.0              | 80.4               |

In addition, Fig. 7 illustrates the stress-strain behavior of deep sea soft clay under different confining pressures. It is shown that the stress-strain behavior exhibits typical strain-hardening development modes regardless of confining pressure ($\sigma_3$). However, deviator stress ($\sigma_1-\sigma_3$) shows a notable rise with increasing confining pressure.

![Stress-strain behavior of deep sea soft clay under different confining pressures](image)

**Fig. 7** Stress-strain behavior of deep sea soft clay under different confining pressures

The results of the pore-water pressure development of deep sea soft clay are shown in Fig. 8 and discussed below. With increasing axial strain, the pore-water pressure gradually increases and shows a two-stage change characteristic: initially, the pore-water pressure rapidly increases, and, subsequently, when the axial strain is approximately 3%, the pore-water pressure enters a slow growth stage.

![Pore-water pressure development of deep sea soft clay under different confining pressures](image)

**Fig. 8** Pore-water pressure development of deep sea soft clay under different confining pressures
The effective stress paths for all tests are presented in the \( p'-q \) diagram in Fig. 9, where \( p'=\frac{(\sigma_1'+2\sigma_3')}{3} \), the effective mean normal stress, is assigned to the horizontal axis, and \( q=(\sigma_1'-\sigma_3) \), the deviator stress, is plotted on the vertical axis. The effective stress paths obtained for different confining pressures indicate similar behavior; it can be observed that the sample initially contracts, generates positive pore-water pressure (the effective stress path leans throughout the loading to the left of vertical), passes through a phase-transformation state, and then dilates with the same stress ratio. The failure points from these three tests lie on a line (the critical-state line) that passes through the origin of the \( p'-q \) chart.

![Fig. 9 The \( p'-q \) relationship curves of deep sea soft clay](image)

6 Conclusions
(1) Compared with soft dredger fill, deep sea soft soil is an inorganic clay of high plasticity, high natural water content, with more quartz and less clay minerals. In addition, deep sea soft clay and soft dredger fill have particularly similar particle size compositions and belong to poorly graded soils with large amounts of clay particles.
(2) As regards the compression behavior, the compressive deformation of deep sea soft clay is slightly larger than that of soft dredger fill, while the coefficient of compressibility \( a_{1,2} \), modulus of compressibility \( E_{s,1-2} \), and compression index \( C_c \) of the two types of soil are approximately the same.
(3) The stress-strain behavior of deep sea soft clay and soft dredger fill exhibits typical strain-hardening characteristics, and the elastic modulus and failure strength of the two types of soils are basically similar.
(4) The results reveal that deep sea soft clay and soft dredger fill show a particularly high similarity in terms of mineral composition, particle size composition, physical properties, and mechanical characteristics. Therefore, in future experimental research, it may be important to explore the basic characteristics of deep sea soft clay using the soft dredger fill combined with deep sea occurrence environment.

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