Experimental study on the micro-mechanism for strength degradation of deep-sea soft soil

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Abstract. In this study, the cyclic strength degradation mechanism of deep-sea soft soil is investigated from a microscopic perspective. To explore this problem, a series of cyclic penetration tests are carried out for reconstituted soil by proved T-bar penetrometer to obtain the variations of strength under cycle loading. The undrained shear strength for reconstituted deep-sea soft soil degrades under cycle loading and eventually tends to be stable. At the same time, the SEM images are got at different stages. A new quantitative evaluation parameter of microstructure (probability entropy, $H$) is defined to analyze the changes of soil microstructure. In the continuous cyclic penetration process, the $H$ of reconstituted deep-sea soft soil first increases and decreases after a maximum value. Based on the T-bar penetrometer tests and probability entropy results, the cyclic strength degradation mechanism is proposed. The process of cyclic strength degradation is that the microstructure is constantly destroyed, and eventually a stable structure with uniform particle shape and direction is formed.

1. Introduction

Deep-sea soil is generally located at a depth of more than 1,000 meters below sea level. Due to the special sedimentary environment and material composition, deep-sea soft soil has different properties [1]. Its physical state is soft or fluid. The mechanical properties of deep-sea soft soil are characterized by low strength. In recent years, more and more subsea structures are being constructed. These weak seabed foundations are often subjected to cycle loading [2-4]. The complex loading conditions make the deep-sea soft soil cyclic strength degradation problem very prominent [5]. In actual engineering, if this is not considered, the safety and stability of deep-sea projects will be seriously threatened. Therefore, it is necessary to explore the mechanism of cyclic strength degradation mechanism of deep-sea soft soil. With the development of modern testing technology, scanning electron microscope (SEM), CT, NMR and other advanced technologies [6-8] has been widely used in the field of geotechnical engineering. Scanning electron microscope images can clearly observe the shape and orientation of soil particles and
pores which can determine changes in microstructure. The current research on microstructure is mostly qualitative analysis. Especially for deep-sea soft soil, there is no suitable indicator to quantify the changes of microstructure.

For deep-sea soft soil, a series of cyclic penetration tests are carried out by improved T-bar penetrometer to obtain the variations of strength under cycle loading. At the same time, a large number of SEM images are got at different stages. Based on the experimental data, a new quantitative evaluation parameters of microstructure is proposed to analyze the changes of soil microstructure. Finally, a mechanism is discussed based on the experimental findings to explain the cyclic strength degradation phenomenon.

2. Experimental program

2.1 Soil samples
The deep-sea soft soil used in this study were obtained from the seabed in the South China Sea (SCS) (see Figure 1). The soil sample was collected by gravity piston corer of 110mm diameter. The retrieved soil appears to be saturated, very plastic dark gray clay. Its water content exceeds the liquid limit. Detailed basic properties are presented in Figure 2 and Tables 1. According to the liquidity index and plasticity chart based on the Unified Soil Classification System (USCS) [9], the deep-sea soft soil in this study is divided into elastic silt (MH).

![Fig.1 Location of the soil sites in SCS](image1)

| Table 1 Basic properties of the deep-sea soft soil |
|-----------------------------------------------|
| Index  | Specific gravity | Moisture content | Liquid limit | Plastic limit | Liquid index | Void ratio |
|--------|------------------|------------------|--------------|---------------|--------------|------------|
| Deep-sea soft soil | 2.65~2.75 | 97.8~117.9 | 80.6~114.3 | 46.3~69.8 | 1.1~1.5 | 2.9~3.6 |

The reconstituted deep-sea soft soil samples were made as follows. Firstly, the soil was air-dried. Secondly, it was stirred with distilled and de-aired water in a vacuum. The water content is 1.5 times liquid limit. Thirdly, the obtained slurry poured into a cylindrical strongbox (diameter 140 mm, height 200mm). Finally, the slurry was consolidated under the vertical stresses (7.5kPa) which are the same as those in its natural sedimentation state (Fig.3). After a period of 30 days, the reconstituted deep-sea soft soil was prepared completely.
2.2 Improved T-bar penetrometer testing apparatus

The T-bar penetration is crucial for evaluating the undrained shear strength. The specific structure of T-bar penetration is shown in Figure 4. The measurement of the T-bar penetrometer is 24mm in length and 5mm in diameter. A motor controller is set to control the displacement rate. In the penetration test, the penetrometer is pushed into the samples. A guide can guarantee the verticality. The displacement of the T-bar probe is recorded. In this study, 2 mm/s is selected as the displacement rate. The cyclic penetration tests were exerted on reconstituted deep-sea soft soil samples. A totally ten cycles were carried out in this article.

2.3 Soil microstructure test methods

The evolution of reconstituted deep-sea soft soil sample was observed by the scanning electron microscopy (SEM, NOVA NanoSEM 450 type, FEI Company, USA) under different cycles. In this paper, the microstructure of the sample was observed after 0, 1, 5, and 10 cycles penetration. The samples was cut into block of 10mm×10mm×10mm by knife. The method of freezing dry was used to preserve samples non-destructively.
3. Test results and analysis

3.1 Penetration-extraction resistance in the cyclic penetration tests

![Fig.5 Cyclic T-bar penetration resistance of deep-sea soft samples with depth](image)

![Fig.6 Normalized cyclic strength degradation curves of samples](image)

The penetration resistance of T-bar ($q_{T\text{-bar}}$) is determined as follows [10].

$$q_{T\text{-bar}} = q_m - \left[ \sigma_v - u \left( 1 - a \right) \right] \frac{1}{A_R}$$  \hspace{1cm} (1)

In which, $q_m$ is the measured penetration resistance; $\sigma_v$ is the overburden stress; $u$ is the measured pore water pressure; $a$ is the area ratio that accounts for the water pressure acting on the back of the T-bar penetrometer through the filter element; $A_R$ is the area ratio ($A_R=A_T/A_p$, with $A_T$ and $A_p$ representing the area of T-bar and the probe shaft).

The cyclic penetration test results $q_{T\text{-bar}}$ for reconstituted soil samples are presented in Fig. 5. Whether it
is penetration or extraction, $q_{T-bar}$ reduces with increasing cycle number. On the first cycle of penetration-extraction, the T-bar penetration resistances are maximum. The initial $q_{T-bar}$ of the deep-sea soft soil sample is only 27kPa. The same phenomenon can be observed in soil samples from other three sites. Cyclic penetration-extraction loading causes $q_{T-bar}$ to decrease continuously. After 10-cycle penetration, all the samples are fully disturbed. Resistance to both penetration and extraction keeps constant. At this time, the penetration curve and the extraction curve are completely symmetrical about the zero penetration axis. The residual penetration reaches the lowest value. The normalized cyclic strength degradation curve is shown in Figure 6. The cycle resistance ($q_{ini}$) is normalized by the initial penetration resistance ($q_{ini}$). The strength degradation of samples can apparently be found.

3.2 Evolution of soil microstructure

3.2.1 Qualitative analysis of soil microstructure in the cyclic penetration tests

![Fig. 7 SEM images of reconstituted soil sample at four stages of cyclic penetration.](image)

(a) Prior to test. (b) After 1-cycle penetration. (c) After 5-cycle penetration. (d) After 10-cycle penetration.

The SEM observations of deep-sea soft soil from site 1 are shown in Figure 7. They show the microstructure alteration of reconstituted soil after different number cycle of penetration. In Figure 7, the evolution of reconstituted deep-sea soft soil microstructure can be observed. The clay plate shows a
preferred parallel packing in Figure 7a. This structure arranges densely and exhibits directional. The large-sized clay plate aggregates prevail in the reconstituted soil microstructure. The reconstituted samples contain numerous small inter-aggregate pores. The most shape of the inter-aggregate pores is stable triangles and oblate circles. After 1-cycle penetration, the initial dense packing structure is been partially disturbed (see Figure 7b). Some large-sized clay plate aggregates are destroyed and start getting small. The distance between the clay plate aggregates increases. The particles start to become loose and disordered. The original small inter-aggregate pores began to become large pores. When the reconstituted sample experiences 5-cycle penetration (see Figure 7c), the large and small size particles prevail. The clay plate aggregates get most disordered. The shape of large sized inter-aggregate pores changes into more complex polygons. From 5-cycle penetration to 10-cycle penetration (see Figure 7d), the remaining large particles and pores are divided into small ones. At the same time, the particles move and rotate directionally. Particle directions tend to be uniform. The structure becomes dense under cycle loading. The inter-aggregate pores also become uniform and distributed widely.

3.2.2 Proposal of probability entropy

![Fig. 8](image)

**Fig. 8** Definition of soil particle size and orientation

In this part, a new quantitative evaluation parameter of microstructure is defined to analyze the changes of soil microstructure in the cyclic penetration test. It is called probability entropy ($H$). It can be used to quantify the soil particle shape and orientation per unit area during the cyclic penetration tests. It can be written as follows.

$$ H = A \times H_d + B \times H_\theta $$

(2)

$$ H = A \times \left( -\sum_{i=1}^{n} \frac{d_i}{M} \ln \left( \frac{d_i}{M} \right) \right) + B \times \left( -\sum_{i=1}^{m} \frac{\theta_i}{M} \ln \left( \frac{\theta_i}{M} \right) \right) $$

(3)

In which, the probability entropy $H$ includes two parts, $H_d$ and $H_\theta$ respectively. They represent the shape and orientation of soil particles. In Eq. (2) ~ (3), several characteristic values are defined as follows: $A$ and $B$ are the weight of $H_d$ and $H_\theta$, $M$ is the total number of soil particles in the statistical area; $d$ (see Fig 8) is the equivalent diameter of each soil particle, which describes the shape of the particles; $n$ is the number of intervals divided by the particle according to the size of $d$; $d_i$ is the number of particles in each interval; $\theta$ is the angle between the major axis of the soil particle equivalent ellipse and the positive direction of the X-axis, which describes the orientation of the particles; $m$ is the number of intervals divided by the particle according to the size of $\theta$; $\theta_i$ is the number of particles in each interval. In this article, $A$ and $B$ are both 0.5. The particle size $d$ will be divided into 5 intervals ($n=5$), which are 0~1μm,
1~2μm, 2~5μm, 5~10μm, >10μm, while θ (0°-180°) will be divided into 18 intervals (m=18), whose angle is 10°. The value of $H$ ranges from 0 to 1. The larger value of $H$ is, the more disordered the particles are arranged.

3.2.3 Quantitative analysis of soil microstructure in the cyclic penetration tests

Fig. 9 Evolution of probability entropy $H$ with loading cycle number.

Based on the SEM images as shown in Fig 6, the probability entropy can be obtained. The calculation results and curves are respectively indicated in Fig 9. They can show the value and trend of the probability entropy clearly.

The probability entropy curve shape of deep-sea soft soil is parabola whose opening goes down. It is clearly seen that the probabilistic entropy first increases and decreases after a maximum value. The change of $H_d$ and $H_0$ also tend to be the same with $H$. For example, the $H$, $H_d$ and $H_0$ of deep-sea soft soil is 0.793, 0.705 and 0.882 respectively under no penetration. The initial penetration load makes the $H$ increase from 0.793 to 0.810. Then $H$ tends to reach a maximum peak ($H=0.842$) after 5-cycle penetration. $H_d$ and $H_0$ also increase from 0.723, 0.897 to 0.761, 0.924 which are maximum. From the 2nd to the 5th penetration, the change in the probability entropy is significantly smaller than that from the 0th to the 2nd penetration. It’s obvious that a certain drop happens to $H$ during last 5 cycles penetration. The final probability entropy is 0.827, meanwhile $H_d$ and $H_0$ are 0.754, 0.899.

4. Discussion: Cyclic strength degradation mechanism of deep-sea soft soil

Fig. 10 The cyclic strength degradation mechanism of deep-sea soft soil in microstructure.
The macro-mechanical behavior of soil is closely related to the change of micro-structure. The engineering characteristics of deep-sea soft soil are a comprehensive reflection of the adjustment and evolution of the constituent elements of the microstructure. In this section, the experimental results of improved T-bar penetrometer and SEM images are utilized to comprehensively and systematically discuss the cyclic strength degradation mechanism of deep-sea soft soil. It is expected to fundamentally understand the characteristics of soil cyclic strength degradation.

The cyclic strength degradation properties of deep-sea soft soil are more significant. Some existing theories cannot explain the cyclic strength degradation of deep-sea soil well. The proposition of probability entropy can help us quantitatively describe the microstructure changes of soil. Through the analysis of the calculation results of probability entropy, it’s not hard to get the cyclic strength degradation mechanism for reconstituted deep-sea soft soil.

Under cycle loading, the microstructure evolution of reconstituted deep-sea soft soil can be divided into two stages (see Fig 10). The action of cycle loading causes a stable structure to transform into an unstable structure. After that, the following cyclic loading makes the unstable structure eventually form a new stable structure. Pre-consolidation enhances soil particle orientation showing a horizontal distribution [11]. And the size of particle is large. The probability entropy of reconstituted soil is the smallest before loading. The first stage of the cycle loading process is that large clay plate aggregates are gradually broken into small ones, and then become disordered. The probability entropy increases and reaches its maximum value. After the first stage, the large and small size particles prevail. Particles are disordered. The structure is unstable after the first stage of loading. The second stage is mainly the process of structural regeneration. The remaining large particles are divided into small ones. The orientation of the particles tends to be consistent by moving and rotating under loading. The microstructure is denser. Therefore, the probability entropy decreases to a certain extent after the maximum point. The cyclic strength degradation of reconstituted deep-sea soft soil is the process that stable microstructures are destroyed into unstable structures, and finally form a stable structure.

5. Conclusions
A series of cyclic penetration tests is carried out to investigate cyclic strength degradation of deep-sea soft soil by an improved T-bar penetrometer. The evolution of soil microstructure is observed by SEM images. Based on the testing results, a new quantitative evaluation parameter of microstructure (probability entropy, $H$) is defined to analyze the changes of soil microstructure. The main concluding remarks can thus be drawn as follows.

In the cyclic penetration tests, the undrained shear strength of reconstituted deep-sea soft soil degrades under cycle loading. After the cyclic penetration tests, the undrained shear strength of them reaches a stable value.

Probability entropy, $H$ is proposed to analyze the changes in soil microstructure. In the continuous cyclic penetration process, the $H$ of reconstituted soil, the $H$ first increases and decreases after a maximum value. The cyclic strength degradation of intact deep-sea soft soil is the process that the metastable microstructure collapses until it is completely destroyed and finally to a new stable structure. The size and orientation of the new structure particles tend to be uniform. The process of structural destruction is the process of forming a new structure. Because of dense packing structure, the failure process of reconstituted soil is slow. After the structure was destroyed, the microstructure at this time is a
disordered and unstable structure. The following cycle loading makes the reconstituted soil form a new stable structure. The process of cyclic strength degradation is that the microstructure is constantly destroyed, and eventually a stable structure with uniform particle shape and direction is formed.

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