Experimental investigation of dynamic shear behavior of typical silt sand in Rudong Offshore Wind Farm

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Abstract. The dynamic properties of typical silt sand in offshore wind farm are closely related to the stability of offshore wind farm foundations. This study investigates the dynamic behavior of typical silt sand in Rudong offshore wind farm of Jiangsu province based on dynamic triaxial testing and resonant column testing. Specifically, the dynamic properties including dynamic modulus, damping ratio, dynamic strength, dynamic strain, dynamic pore water pressures and stress-strain relationship of the silt sand are studied. It is found that the accumulated strain and pore pressure continuously increase with the increased cyclic number, which eventually leads to liquefaction failure. Soil specimen with a higher confining pressure is more likely to reach liquefaction with a lower number of loading cycles. It is also found that the Hardin-Drnevich model can be used to reflect the mechanism of the effect of confining pressure on the dynamic behavior of the silt sand. The dynamic shear modulus and damping ratio decrease and increase exponentially with the increase of shear strain, respectively.

1. Introduction

The recent years have witnessed the rapid development of offshore wind energy of China. Several offshore wind power experimental prototypes have been built [1-2]. For example, the world’s first offshore wind farm outside of Europe, Shanghai Donghai Bridge 100MW offshore wind power demonstration project was built in July 2010 [3-4]. On December 30, 2010, all 134 1.5MW generating units of the 201MW wind farm along the beach line of Xiangshui, Jiangsu Province were connected to the grid for power generation.

Particularly, the 150 MW offshore (intertidal zone) demonstration wind farm in Rudong, Jiangsu is located in the intertidal zone and offshore waters of the eastern coast of Rudong County, Jiangsu Province. The Quaternary sedimentary strata are scattered throughout the site from the surface of the soil to the depth of the survey borehole (about 70m) and are dominated by silt.

At present, there is a lack of studies reporting the engineering characteristics of silt and sand in this area, which are particularly important for the design of offshore wind farm foundations. This is because the foundation soil is subjected to complex loading and unloading during the construction and normal operation of the offshore wind turbine. Meanwhile, the foundation structure is inevitably subjected to periodic loads such as waves and mechanical vibration of the wind turbine, as well as wind loads and potential dynamic effects such as earthquake load [5-6]. Particularly, when the soil is under small strain conditions, its mechanical properties and modulus exhibit nonlinear variations with...
the change of strains [7-8]. These properties have induced great uncertainties to the field monitoring and safety evaluations [9-10].

This paper presents an experimental investigation of the mechanical properties of silt in this region under complex dynamic loading conditions. The results can enhance our understanding of the engineering properties of typical silt in this region and provide technical support for the improvement of winged single pile structure, solidification, and treatment of surface soil.

2. Test samples and test plan

2.1. Test samples

The soil samples of this study are all remolded silt samples from superficial stratigraphic. The sampling location is determined based on the information provided in the survey report. In this study, 78 remodeled soil samples are produced. All experimental soil samples are vacuum-saturated after the completion of the sample preparation, and the relevant experiments are carried out after the saturation exceeds 98%. The samples are produced with a size of 50×100 mm (diameter×height) for the stress path triaxial tests and the resonance column tests. For the dynamic triaxial tests, the samples have a size of 70×140 mm (diameter×height).

Fig. 1 depicts the particle size distribution of the test soil. The d60, d30, d10, Cu and Cc of the soil is 0.076 mm, 0.04 mm, 0.018 mm, 4.22 and 1.17, respectively. The soil has a clay content of 5.2% and a sand content of 41%. It is primarily composed of very fine sand (i.e., 0.074 ~ 0.1mm), with very little medium-coarse sand. Therefore, the soil sample is a silty soil. The specific gravity Gs of the soil is 2.70. The soil samples have a dry density and void ratio of 1.55 g/cm3 and 0.72, respectively, which are relatively dense silt samples.

2.2. Dynamic triaxial test

This paper contains two research objectives regarding the dynamic characteristics of the silt. The first one is to determine the dynamic strength, (i.e., dynamic strength curve and liquefaction stress ratio) of the typical silt. This is helpful to the analysis of foundation stability under dynamic loads that may result in medium to large structure deformation (e.g., strain is larger than 10^{-4}). This is achieved by carrying out experiments using the GCTS dynamic triaxial test system. The other one is to determine the dynamic modulus and damping ratio of the silt, which is useful to the estimation of changes in displacement, velocity, acceleration, and stress of the soil within a certain range caused by periodic loads with time. This study uses the GCTS dynamic triaxial test system and the GDS-RCA resonance column device to measure the dynamic modulus and damping ratio of the soil at medium to large strain levels (e.g., 10^{-4}∼10^{-2}) and small strain levels (10^{-6}∼10^{-4}), respectively.
The dynamic characteristics of soil are mainly affected by the confining pressure level, the number of cyclic loadings, and the consolidation path. The number of cyclic loadings is controlled by the magnitude of the dynamic load and the selected soil sample failure standard. Generally, it is not controlled as a test design factor. Specimens are tested under two different consolidation ratios, three confining pressure levels (i.e., 100 kPa, 200 kPa, and 300 kPa) and three dynamic load levels, respectively to measure the dynamic strength of the soil. In total, 18 (i.e., 2×3×3=18) specimens are prepared for the consolidated and undrained (CU) triaxial shear test. The initial conditions for testing the soil dynamic strength are summarized in Table 1. Similarly, the dynamic elastic modulus and damping ratio (medium strain level 10^{-4}~10^{-2}) test considers two different consolidation ratios, three confining pressure levels (i.e., 100kPa, 200kPa, and 300kPa) and 4 different dynamic load levels, requiring a total of 2×3×4=24 specimens for the consolidated and undrained (CU) triaxial shear test, as shown in Table 2.

Isotropic consolidation and anisotropic consolidation with Kc=1.5 are implemented for the specimen consolidation, respectively. The dynamic load has a sinusoidal waveform with a load frequency of 1 Hz, which is determined according to relevant specifications and literature.

| Group | Test No. | consolidation path | Confining pressure (kPa) | Dynamic load levels |
|-------|----------|-------------------|--------------------------|--------------------|
| 1     | N1-1     | isotropic         | 100                      | 1, 2, 3            |
| 2     | N1-2     | isotropic         | 200                      | 1, 2, 3            |
| 3     | N1-3     | isotropic         | 300                      | 1, 2, 3            |
| 4     | N2-1     | Kc=1.5            | 100                      | 1, 2, 3            |
| 5     | N2-2     | Kc=1.5            | 200                      | 1, 2, 3            |
| 6     | N2-3     | Kc=1.5            | 300                      | 1, 2, 3            |

| Group | Test No. | Consolidation path | Confining pressure (kPa) | Dynamic load levels (dynamic strains) |
|-------|----------|--------------------|--------------------------|--------------------------------------|
| 1     | D1-1     | isotropic         | 100, 200, 300            | 10^-4                                |
| 2     | D1-2     | isotropic         | 100, 200, 300            | 10^-3.5                              |
| 3     | D1-3     | isotropic         | 100, 200, 300            | 10^-2.5                              |
| 4     | D1-4     | isotropic         | 100, 200, 300            | 10^-2                                |
| 5     | D2-1     | Kc=1.5            | 100, 200, 300            | 10^-4                                |
| 6     | D2-2     | Kc=1.5            | 100, 200, 300            | 10^-3.5                              |
| 7     | D2-3     | Kc=1.5            | 100, 200, 300            | 10^-2.5                              |
| 8     | D2-4     | Kc=1.5            | 100, 200, 300            | 10^-2                                |
2.3. Resonance column test
Under the small strain conditions, 2 groups of resonance tests are performed referring to relevant
specifications and literature. Each test group contains specimens with 5 confining pressure levels (i.e.,
100kPa, 200kPa, 300kPa, 500kPa and 700kPa). For each test, 5~9 excitation loads are applied to
obtain the dynamic shear modulus and damping ratio data corresponding to different dynamic shear
strains. Table 3 shows the detailed information of resonance column test.

| Group No. | 1 | 2 |
|-----------|---|---|
| Specimen No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Confining pressure (kPa) | 100 | 200 | 300 | 500 | 700 | 100 | 200 | 300 | 500 | 700 |

3. Dynamic property analysis

3.1. Accumulated deformation
Fig. 2 shows the relationship between the cumulative deformation of marine sedimentary silt and the
number of cycles under different maximum dynamic stresses. It can be seen from the figure that the
load frequency is 1Hz. When the dynamic stress ratio $\sigma_d/\sigma_0$ is 0.8~1.0, the cumulative strain increases
with the increase of the number of cycles until liquefaction failure occurs at a cumulative strain of
higher than 10%. When the confining pressure is 100 kPa, the dynamic stress ratio $\sigma_d/\sigma_0$ of the soil is
0.9 and 1.0, and the number of cyclic vibrations experienced by the soil liquefaction failure are 397
and 184, respectively. With the increase of the number of cycles, the cumulative strain increases, and
the pore water pressure also increases, which finally leads to the liquefaction of the soil. With the
increase of the confining pressure, the number of cyclic loads experienced by the soil to reach
liquefaction failure is also continuously reduced.

Fig. 3 depicts the influence of the dynamic stress ratio on the cumulative deformation. The residual
accumulated strain of the soil and its increase rate are positively correlated with the ratio of the applied
stress. In addition, the sample curve is of destructive type, i.e., the axial strain increases monotonously
and does not tend to be stable. Moreover, the residual cumulative strain of the soil and its increase rate
are positively correlated with the ratio of the dynamic stress. Under the same conditions of confining
pressure, frequency, vibration frequency, etc., the higher the cyclic stress ratio level, the greater the
dynamic strain produced by the soil sample. In other words, the higher the cyclic stress ratio, the fewer
cyclic vibration times required for the soil sample to fail.

![Figure 2. Cumulative strain versus cyclic numbers under different confining pressures and cyclic stresses](image-url)
3.2. Dynamic stress-strain curve and its characteristic index

When studying the dynamic deformation characteristics of soil, the time course of dynamic stress $\sigma_d$ (or $\tau_d$), dynamic strain $\varepsilon_d$ (or $\varepsilon_d$) and dynamic pore pressure $u_d$ acquired from the dynamic triaxial test can be used to sort out the backbone curve and hysteresis curve that represent the law of deformation. Generally, the dynamic deformation characteristic index of soil includes the dynamic modulus $E_d$ or $G_d$ representing the characteristics of the backbone curve and the damping ratio $\lambda$ representing the characteristics of the hysteresis curve. Dynamic modulus and damping ratio are the two basic parameters of the equivalent linear viscoelastic model (Hardin-Drnevich model).

Fig. 4 presents a scatter diagram and a fitting curve of dynamic elastic modulus $E_v$.s. dynamic strain $\varepsilon_d$. There is a good correlation between the dynamic elastic modulus and the dynamic strain. The confining pressure has little effect on the dynamic elastic modulus. Under small dynamic strain levels, the dynamic elastic modulus is sensitive to dynamic strain, and it decreases exponentially with the increase of dynamic strain. When the dynamic strain reaches about 1%, the dynamic elastic modulus tends to be stable.

3.3. Variation curves of dynamic shear modulus and damping ratio

The dynamic shear modulus $G$ and damping ratio $D$ of the soil at small strains ($10^{-6}$~$10^{-4}$) are determined based on the resonance column tests. They vary with the magnitude of the dynamic shear strain. They are measured based on the resonance column when the strain is lower than $10^{-4}$. They are obtained by fitting the data of both the resonance column test results at shear strain smaller and larger than $10^{-4}$ using the Hardin-Drnevevich model when the shear strain is higher than $10^{-4}$. 

Figure 3. Influence of dynamic stress ratio on the cumulative strain.

Figure 4. Scatter diagram of $E$ versus $\varepsilon_d$ of the specimen under a confining pressure of 100 kPa
In order to determine the shear modulus at any consolidation pressure and any shear strain, the $G$-$\gamma$, $D$-$\gamma$ curves are normalized to derive the relationship curve among the shear modulus ratio $G/G_{\text{max}}$, damping ratio $D$ and the normalized shear strain $\gamma/\gamma_r$. According to the Hardin-Drnevich model, the dynamic shear stress $\tau$ and the shear strain $\gamma$ satisfy Eq. (1):

$$
\tau = \gamma/(1/G_{\text{max}} + \gamma/\tau_y).
$$

Therefore, the dynamic shear modulus $G$ of the soil is:

$$
G = 1/(1/G_{\text{max}} + \gamma/\tau_y).
$$

We have $G/G_{\text{max}} = 1/(1 + \gamma/\gamma_r)$, where $\gamma_r = \tau_y/G_{\text{max}}$ is the reference shear strain, and $\tau_y$ and $G_{\text{max}}$ are parameters related to soil properties. The reference shear strain $\gamma_r$ and the maximum shear modulus $G_{\text{max}}$ of each layer of soil samples under different consolidation pressure $\sigma_3$ can be calculated by fitting the test results. The maximum dynamic shear modulus $G_{\text{max}}$ and the average consolidation stress $\sigma_m$ satisfy Eq. (3):

$$
G_{\text{max}} = kp_a \left( \frac{\sigma_m}{p_a} \right)^n.
$$

Fig. 5 shows the variation of the dynamic shear modulus $G_d$ with the shear strain $\gamma$ under different confining pressure, as well as the corresponding fitting curves. The dynamic shear modulus has a good correlation with the dynamic shear strain: it decreases exponentially with the increase of the dynamic shear strain. At low dynamic shear strain levels, the dynamic shear modulus maintains nearly a constant value, when the dynamic shear strain increases to a certain value, the dynamic shear modulus begins to drop sharply. In addition, the dynamic shear strain is greatly affected by the confining pressure. As the confining pressure increases, the maximum dynamic shear strain also increases. The increase in confining pressure leads to an increase in the compactness of the soil and the ability to resist shear forces. As a result, the dynamic shear modulus increases accordingly. From Fig. 8b we can see that the damping ratio and the dynamic shear strain can be well fitted with an exponential function. The damping ratio increases with the increase of the dynamic shear strain. Overall, the damping ratio is not significantly affected by the confining pressure.

Figure 5. Variation of shear modulus and damping ratio with shear strain: (a) $G_d$ v.s. $\gamma$; (b) $\lambda$ v.s. $\gamma$

4. Conclusions

In this paper, dynamic triaxial tests and resonance column tests are performed to investigate the dynamic mechanical properties of typical silt soils in the 150 MW offshore (intertidal zone) demonstration wind farm in Rudong, Jiangsu province of China. The cumulative law of dynamic strain and the attenuation law of shear modulus of the silt under different confining pressures are comprehensively analyzed. The following conclusions are obtained:

1) When the soil dynamic stress ratio $\sigma_d/\sigma_0$ is 0.9 and 1.0, the number of cyclic vibrations experienced by the soil liquefaction failure are 397 and 184, respectively. With the increase of the
number of cycles, the cumulative strain and pore water pressure increase, which finally leads to the liquefaction of the soil.

2) Under cyclic loading, the test specimens require a high dynamic stress ratio to reach the dynamic failure state. The dynamic modulus has a strong correlation with the dynamic strain amplitude, which can be fitted with a power function or an exponential function. The damping ratio has a good correlation with the dynamic strain amplitude in small dynamic strain levels and can be fitted with an exponential function. However, the correlation is low at medium dynamic strain levels.

3) The resonance column test results indicate that the dynamic shear modulus and damping ratio of the soil at small strains (10⁻⁶⁻⁻⁻⁻¹⁰⁻⁴) decay and increase exponentially with the increase of shear strain, respectively.

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