Ocean Engineering 129 (2017) 191–202

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Cyclic response of natural soft marine clay under principal stress rotation as induced by wave loads

Yuke Wang[a,b,c], Yufeng Gao[c,d], Lin Guo[e,*], Yuanqiang Cai[f], Bing Li[g], Yue Qiu[h], Ali H Mahfouz[i]

[a] College of Water conservancy and Environmental Engineering, Zhengzhou University, No. 100, Science Avenue, Zhengzhou 450001, PR China
[b] Collaborative Innovation Center of Water Conservancy and Transportation Infrastructure Safety Protection, Henan Province, Zhengzhou University, Zhengzhou, Henan 450001, PR China
[c] Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, No. 1, Xikang Road, Nanjing 210098, PR China
[d] Jiangsu Research Center for Geotechnical Engineering Technology, Hohai University, No. 1, Xikang Road, Nanjing 210098, PR China
[e] College of Architecture and Civil Engineering, Wenzhou University, Wenzhou 325035, PR China
[f] Key Laboratory of Soft Soils and Geoenvironmental Engineering, Ministry of Education, Zhejiang University, Hangzhou 310027, PR China
[g] College of Civil Engineering, Southeast University, Nanjing 210096, PR China
[h] Shandong University of Science and Technology, Qingdao 266590, PR China
[i] Faculty of Petroleum and Mining Engineering, Suez University, Egypt

## ARTICLE INFO

*Keywords:*
Principal stress rotation
Hollow cylinder apparatus
Natural soft marine clay
Pore water pressure
Axial strain
Degradation

## ABSTRACT

In order to investigate the cyclic deformation behavior of natural soft marine clay under the general stress condition, which is due to travelling waves involved principal stress rotation, a series of undrained tests were carried out by using GDS hollow cylinder apparatus (HCA). The principal stress axis rotates continuously while holding the deviator stress (difference between the vertical normal stress and horizontal normal stress) at a constant level. The tests results show that, the pore water pressure, stress-strain hysteretic loop, dynamic modulus of the tested samples are significantly dependent on *CSR*s and confining pressures. Furthermore, pore water pressure generates slightly during the first 30 cycles, and accumulates with the increase of cycles. The tensile axial strain occurs in the initial loading cycles and the development styles are various with different *CSR*s and confining pressures. With the larger *CSR*s and confining pressures, higher strain degradation occurs. A new critical value between 0.16 and 0.18 is suggested for *CSR* under continuous principal stress rotation.

## 1. Introduction

Soft marine clay is widespread in Wenzhou, a coastal city in China. Being one of the most developed areas in China, a large number of infrastructures have been constructed on this kind of soil. The soil grounds of these projects may undergo long-term cyclic loads caused by wave loads, traffic loads, earthquake, etc. during construction and operation period. Ocean structures that are built on soft marine soil foundation are subjected to great damage due to the settlement and large deformation leading by the soil strength weakening of soil foundation and reduction of the bearing capacity. For example, in Yangtze Estuary of China, due to wave and strong storms, a breakwater sinks into the soil in part or several meters deep, or offset the original position about 20 m away during construction of caisson. The soil grounds of these projects may undergo long-term cyclic wave loads during construction and operation period. Obviously, the cyclic deformation behavior of soft marine clay is one of the major concerns in geotechnical engineering. For guaranteeing the safety and normal use of these structures, it is necessary to investigate the cyclic response of the soft marine clay.

Serious efforts have been made to investigate the dynamic properties of saturated soft clay by triaxial apparatus (Moses et al., 2003; Chen et al., 2004; Li et al., 2011; Wang et al., 2013). However, the conventional triaxial shear apparatus cannot simulate complex stress paths involved continuous principal stress rotation. Many field loading situations, such as wave loading situations, on seabed deposits, multi-directional earthquake loading in level ground, and lateral cyclic loading on the soil behind retaining structures, involve rotation of the principal stress directions (Yang et al., 2007). A series of hollow cylinder tests on normally consolidated soft clay with and without principal stress rotation were performed by Xiao et al. (2013), the presence of principal stress rotation increases the cumulative deformation of soft clay by 9–23% compared with that without principal stress rotation. For a long time, the investigations of the soil cyclic deforma-

* Corresponding author.
*E-mail address:* lingpray@163.com (L. Guo).

http://dx.doi.org/10.1016/j.oceaneng.2016.11.031
Received 14 November 2015; Received in revised form 16 November 2016; Accepted 21 November 2016
Available online 24 November 2016

**Nomenclature**

*The following symbols are used in this paper:*

| | |
|---|---|
| $e_o$ | Initial void ratio |
| $G_s$ | Specific gravity |
| $\rho_0$ | Initial density |
| $H$ | Height of the specimen |
| $w_L$ | Liquid limit |
| $I_p$ | Plasticity index |
| $q_{cyc}$ | Cyclic deviator stress |
| $CSR$ | Cyclic stress ratio |
| $p_o$ | Wave amplitude, |
| $L$ | Wave length |
| $T_t$ | Load period |
| $p_o$ | Amplitude |
| $p$ | Confining pressure |
| $W$ | Axial force |
| $z$ | Axial deformation |
| $\sigma_1$, $\sigma_2$, $\sigma_3$ | Major, intermediate, and minor principal stresses |
| $\sigma_z$, $\sigma_r$, $\sigma_\theta$ | Axial, radial, and circumferential stresses |
| $\tau_{z\theta}$ | Shear stress |
| $\gamma_{z\theta}$ | Shear strain |
| $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$ | Major, intermediate, and minor principal strain |
| $\varepsilon_z$, $\varepsilon_r$, $\varepsilon_\theta$ | Axial, radial, and circumferential strain |
| $M_r$ | Dynamic modulus |
| $\varepsilon_{a,\ max}$,$\varepsilon_{a,\ min}$ | Maximum, minimum axial strain |
| $\varepsilon_d$ | Difference between Maximum and minimum axial strain |

tion are mostly focused on the effects caused by earthquake loads. However, the geotechnical problems related to the soft clay under principal stress rotation as induced by wave loads have not been fully understood in the past. With the amount of projects increasing in the coastal areas, the destruction caused by cyclic loads with a long acting time, i.e. wave loads, have been drawn great attention.

Wave load, a special kind of cyclic load with reciprocation for a long time, is different from the static load and the seismic load. The typical wave load has a period of 5–20 s, and contains thousands of cycles, whereas an earthquake induces cyclic stresses with a period of about 0.1–10 s and generally contains only 10–100 cycles (O'Reilly, 1991). According to Ishihara and Towhata (1983), the cyclic variation of vertical stress is 90 degrees out of phase with the cyclic change in the horizontal shear stress. During the cyclic alteration of these two components of shear stress, the soil element is subjected to a continuous rotation of the principal stress direction.

The undrained deformation of soil under continuous principal stress rotation is the utmost concern in many investigations. Ishihara and Towhata (1983) were among the first to seriously examine the effects of rotation of the principal stress directions on the undrained response of saturated sand using cyclic triaxial-torsional shear tests. The results indicates that the continuous principal stress rotation exert some influence on the development of excess pore water pressure and the failure of sand during cyclic loading. Miura et al. (1986) considered that the shear deformation of sand due to the rotation of principal stress axis are cannot be negligible, and the effects of inherent anisotropic fabric on the shear deformation and volume change behavior are considerably large. Nakata et al. (1998) found that pore pressures and strains in excess of 5% were accumulated under the cyclic rotation of principal stresses although the deviator stress remains constant.

However, all the studies subjected to principal stress rotation mentioned above focused on sand. The researches about the influence of the continuous principal stress rotation on soft clay are limited. Zhou and Xu (2014) found that the pore water pressure was mainly controlled by the shear stress level, and the influences of shear stress level and rotation angle on strain development were remarkable. However, the studies about the soft clay under principal stress rotation above are merely concentrated on the influence factors such as confining pressure and cyclic deviator stress ratio. Xiao et al. (2013) investigated the effects of principal stress rotation on the traffic load-induced settlement of subways in soft subsoil, while the effects of cyclic stress ratios are not taken into account. Wang et al. (2017) investigated cyclic deformation behavior of natural soft marine clay involved principal stress rotation, it was concluded that the effect of principal stress rotation on the axial strain is significant by comparing with the results conducted by cyclic triaxial tests. However, the effects of confining pressure are not taken into account.

The dynamic properties of soft clay during wave loading are affected by many parameters, including cyclic stress ratio (*CSR*), confining pressure, loading frequency, stress history and so on. Based on earlier studies, the *CSR* and confining pressure are dominant in affecting the strain behavior. According to previous studies, excess pore water pressure generates and accumulates in clay, which degrades the clay structure as well as the stiffness and strength of clay (Ishihara and Towhata, 1983; Zhou and Gong, 2001; Yang et al., 2007). The degradation of clays will influence the development of cyclic strain. It is therefore necessary to investigate the cyclic deformation behavior of soft clay under continuous principal stress rotation.

In this study, a series of HCA tests have been carried out to investigate the effects of continuous principal stress rotation on the cyclic response of saturated soft marine clay in Wenzhou, China. The tests have been conducted by controlling the torsional shear stress and the stress difference between the vertical normal stress and horizontal normal stress. During the tests, the deviator stresses were kept constant while rotating the principal stress axis. The development of cyclic axial strain, pore water pressure, stress-strain hysteretic loops, dynamic modulus of the tested samples are evaluated and compared under different *CSR*s and confining pressures.

## 2. Sampling and preparation of specimens

The natural soft marine clay used in this paper was obtained from a pit with the depth of 2–4 m below the ground surface from a site in Wenzhou, a coastal city in eastern China. This type of clay is typically 30–80 m thick and has been recognized as one of the most problematic soils. The natural samples used in this paper are representative of the dynamic properties of soft foundation induced by wave loads. All test samples were obtained by pressing thin-walled tubes (the diameter of 150 mm and the length of 250 mm) slowly into a horizontal bench prepared in the pit. After that, the tubes were excavated and sealed at the ends, and stored in a humidity room until they were used for testing. This method has been adopted by many researchers (Kirkgard and Lade, 1993; Lade and Kirkgard, 2000; Moses et al., 2003; Lunne

**Table 1**
Index properties of tested soft clay.

| Index properties | Value |
|---|---|
| Specific gravity, $G_s$ (g/cm$^3$) | 2.70 |
| Natural water content, $w_n$ (%) | 56–59 |
| Initial density, $\rho_0$ (g/cm$^3$) | 1.68–1.71 |
| Initial void ratio, $e_0$ | 1.55–1.59 |
| Liquid limit, $w_L$(%) | 64 |
| Plasticity index, $I_p$ | 36 |
| Clay fraction, (%) | 55 |
| Silt fraction, (%) | 41 |