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Cyclic strength of saturated sand under bi-directional cyclic loading

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A B S T R A C T

Subject to cyclic loading due to ocean waves and earthquakes, both the shear stress and axial cyclic stress need to be accounted for in the analyses of stress state and cyclic strength. For laboratory soil test, the loading condition can be simulated by performing hollow cylindrical apparatus test, and also the effects of ratios and phase angles between dynamic axial and horizontal shear stress can be considered. In the present study, the maximum shear stress amplitude of soil element is defined as a measure of cyclic strength. Based on the theoretical analysis and experimental tests, this study investigates the influence from the ratios and phase angles on the number of load cycles leading to liquefaction failures. In addition, the characteristics of pore water pressure development are also studied. The theoretical and experimental results indicate that the ratios and phases between the axial dynamic load and torsional dynamic load significantly affect the dynamic strength of sands. Moreover, ratios and phases between the axial dynamic load and torsional dynamic load influence the accumulation speed of pore water pressure significantly. Nevertheless, when the pore water pressure is normalized, the sensitivity of their influences on the pore water pressure development cannot be identified.

1. Introduction

The fast development of worldwide offshore infrastructures such as transportation and power stations has been witnessed by recent years. The stability of seabed under seismic or sea wave loadings therefore becomes one of the key factors that safeguards the important infrastructures. With the extraordinary development of offshore infrastructures such as subsea pipelines, breakwater, offshore platforms, offshore bridges, artificial islands, and under the national strategy of "the Belt and Road Initiatives" with the intention of promoting international economic cooperation, the development of offshore transportation projects and energy related infrastructures will be further enhanced. All those developments require a dedicated consideration and understanding of integrity performance of the associated foundations and structures. It is especially important to study the seabed stability influenced by the cyclic ocean wave and earthquake loading. Moreover, as the ocean wave loading and earthquake loading may occur simultaneously, a combination of those cyclic load effects leads to a consideration of the coupling between vertical and shear force, which is referred to as bi-directional cyclic loading effects.

With regard to the coupling between the vertical and shear force, research focus has been placed on the study of liquefaction influenced by the rotation in principal stresses, usually accompanied by experimental investigations. With an assumption of infinitely thick soil medium, Madsen (1978) presented an analytical solution to calculate the dynamic response of seabed due to the linear ocean waves. Based on Madsen's solution, Ishihara and Towhata (1983) presented a modeling of infinitely propagating harmonic wave and an elastic half space. The calculated dynamic response shows that under the influence of dynamic shear and normal stress, the dynamic stress deviator is constant, and the principal stress axis rotates within 180°, as shown in Fig. 1.

Ishihara and Yamazaki (1980, 1984) and Towhata and Ishihara (1985) performed hollow cylindrical soil tests of sands subject to rotating principal stress. The results show that, under undrained condition, the rotation of principal stress axis causes an increase in pore water pressure of sands, leading to liquefaction. Symes et al. (1984), Nakata et al. (1998) performed tests with rotating axis of principal stress, the results shows a decrease in cyclic strength of the saturated soil when subject to a rotation of cyclic principal stress axis. Recently, Tong et al. (2010), Qian et al. (2016) and Yan et al. (2015) have also conducted the tests on the deformation behaviour of soils subjected to rotating principal stress. Dakoulas and Sun (1991), Boulanger and Seed (1995), and Luan et al. (2005) performed vertical and torsional bi-directional axial coupling tests, conventional tri-axis tests and conventional cyclic torsional shear tests. By comparing the difference among various loading conditions, they presented that, among the three types of strength, the cyclic torsional shear strength is the highest while the strength for the soil samples subject to principal stress with continuous rotating axes is the lowest.

Conventional studies place focus on the influence of wave loading, in which the wave loading and seabed are modelled as infinitely propagating harmonic wave and the semi-infinite elastic half space, respectively. Under this assumption, the maximum shear stress of the soil is kept

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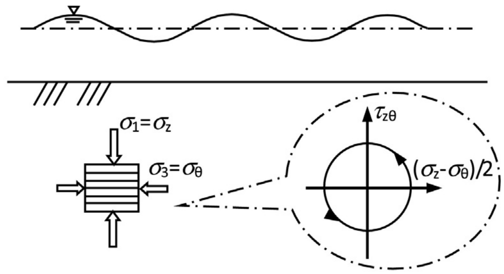

Fig. 1. Rotation of cyclic principal stress axes under ocean wave loading.

constant while the corresponding axes of principal stress are rotating continuously.

In reality, the seabed is far from what a semi-infinite elastic half space can represent. From 90's in the last century, several researchers such as Jeng and Hsu (1996), Hsu and Jeng (1994), Lee et al. (2002), Cha et al. (2003), Hua and Yu (2009) and Zhang et al. (2013) presented analytical solutions with a modeling of finite thickness of seabed. The results show that the thickness modeling of the seabed significantly influences the dynamic response of seabed. In addition, subject to linear regular waves and standing waves, the stress path follows an elliptic shape rather than a circular one. Based on the modeling of finite thickness of seabed subject to wave loading formulated by linear regular wave theory, Wang et al. (2006) stated that, subject to linear regular waves and standing waves, the stress path follows an elliptic shape rather than a circular one. Based on the modeling of finite thickness of seabed subject to wave loading formulated by linear regular wave theory. Wang et al. (2016, 2017) presented an analytical solution to calculate the seabed response, and further proposed that the stress path either followed an elliptic shape or an approximate elliptic shape. The shape and size of the approximate elliptic shape path can be formulated with three characteristic functions.

As a matter of fact, subjected to seismic load, the soil element shows response including both axial and horizontal dynamic shear stress. Assuming that the frequency of bi-directional cyclic loading is constant and the load follows a sinusoidal variation with time, for laboratory soil test, hollow cylindrical torsional shear apparatus can be used to study the complex stress state of soil elements, different amplitude ratios and phase between the axial dynamic stress and dynamic shear stress can be established to achieve elliptic complex loading path. Fig. 2 shows typical loading paths of the dynamic axial stress and horizontal dynamic shear stress due to different combinations in their size and phase.

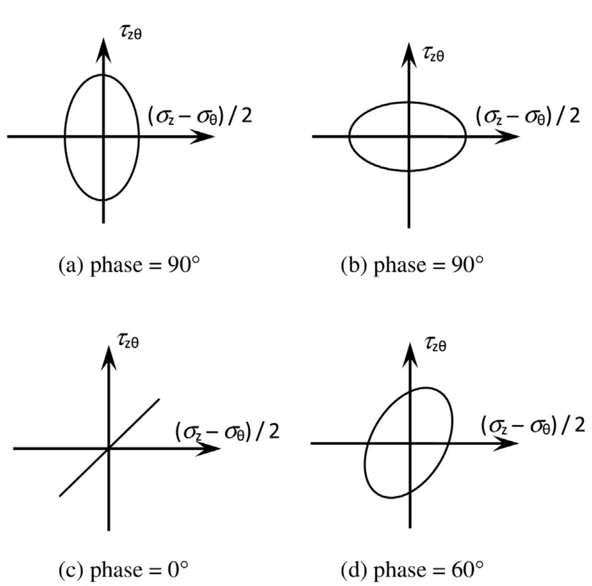

Fig. 2. Load paths associated with different combinations of phase and stress amplitude.

By assuming that the frequency of the axial dynamic stress and horizontal dynamic shear stress is constant, this paper first presents a definition of cyclic dynamic strength. This is followed by a discussion of the number of load cycles to failure for sands influenced by the ratios and phase between the axial dynamic stress and horizontal dynamic stress, provided that cyclic strength is constant for all cases. Furthermore, the discrepancy of the dynamic strengths obtained by the conventional dynamic triaxial test, dynamic torsion-shear test and as well as the axial-torsional bi-directional cyclic load test is explained.

2. Maximum shear stress amplitude and its influence on the cyclic strength

The tests are performed using hollow cylinder apparatus, which comprises 4 major parts: (1) dynamic loading cell; (2) air-water shifting equipment; (3) electronic control system; (4) hydraulic pressure system. The consolidation and loading of soil samples can be realized by independently controlling torque, axial load, and the inner and outer pressure of the cylinder soil samples. Fig. 3 illustrates equipment diagram and stress state of soil element in a hollow cylinder apparatus test.

The axial stress σ_z is calculated as:

$$\sigma_z = \frac{p_o D^2 - p_i d^2}{D^2 - d^2} + \frac{4W}{\pi\left(D^2 - d^2\right)} \tag{1}$$

The radial stress σ_r is:

$$\sigma_r = \frac{p_o D + p_i d}{D + d} \tag{2}$$

The circumferential stress σ_θ is:

$$\sigma_\theta = \frac{p_o D - p_i d}{D - d} \tag{3}$$

The shear stress is $\tau_{z\theta}$ is:

$$\tau_{z\theta} = \frac{12M}{\pi\left(D^3 - d^3\right)} \tag{4}$$

where d and D are the inner and outer diameter of the soil specimen, respectively; p_i and p_o are the internal and external water pressure, respectively; W and M are the applied vertical load and torque, respectively.

The three principal stress components of the soil element are:

$$\sigma_1 = \frac{\sigma_z + \sigma_\theta}{2} + \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + {\tau_{z\theta}}^2} \tag{5}$$

$$\sigma_2 = \sigma_r \tag{6}$$

$$\sigma_3 = \frac{\sigma_z + \sigma_\theta}{2} - \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + {\tau_{z\theta}}^2} \tag{7}$$

From the equation above, it can be derived that the maximum shear stress in the soil element can be calculated as:

$$\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2} = \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + {\tau_{z\theta}}^2} \tag{8}$$

When p_i and p_o are kept constant, and the initial consolidation state follows an isotropic consolidation pattern, the axial dynamic loading and

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