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Cyclic strength of sand under a nonstandard elliptical rotation stress path induced by wave loading*

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Abstract: The principal stress rotation is one of the most important features of the stress state in a seabed subjected to wave loading. Most prior investigations focused their attention on the cyclic behaviour of soil deposits under the circular rotation stress path based on the analytical solutions for a seabed of infinite thickness. In this paper, the nonstandard elliptical, i.e., non-circular, rotation stress path is shown to be a more common state in the soil sediments of a finite seabed with an alternating changeover in stress due to a travelling regular wave. Then an experimental investigation in a hollow cylinder triaxial-torsional apparatus is conducted into the effect of the nonstandard elliptical stress path on the cyclic strength. A special attention is placed on the difference between the circular rotation stress path and the elliptical rotation stress path. The results and observations show that the shear characteristics for the circular rotation stress path in the literature are not applicable for analyzing the cyclic strength of sand in a finite seabed, and also indicate that due to the influence of three parameters about the size and the shape of a nonstandard ellipse, the cyclic strength under a nonstandard elliptical rotation stress path is evidently more complex and diversified as compared with that under a circular rotation stress path. Especially the influence of the initial phase difference on the cyclic strength is significant.

Key words: Principal stress rotation, cyclic strength, nonstandard elliptical rotation stress path, wave loading

Introduction

The wave loading, as one of the most important cyclic loadings on an offshore foundation, generates an alternating changeover of the horizontal shear stress and the stress difference between the vertical and horizontal normal stresses. The wave-induced dynamic response of the seabed has been studied since the early 1970s, and considerable advances have been made on a seabed of infinite thickness. Based on the analytical solution for the seabed of infinite thickness obtained by Madsen[1], Ishihara and Towhata[2] show that under the wave loading, the principal stress in the seafloor sediment rotates continuously and that the corresponding stress path is a circle on the $[(\sigma_z' - \sigma_x')/2, \tau_{zx}]$ plane. Using a hollow cylinder triaxial-torsional apparatus, they made the first attempt to characterise the undrained behaviour of the saturated sand influenced by the principal stress rotation in experiments. Their tests show that under the undrained condition, even if the magnitude of the cyclic shear stress is constant, the continuous rotation of the principal stress directions can lead to the generation of an excess pore water pressure and the accumulation of shear strains. Meanwhile, the cyclic strength of the sand under a rotational shear is less than that obtained from conventional cyclic triaxial tests using hollow cylinder specimens. Since the work of Ishihara and Towhata[2], numerous similar experiments[3-13], which can be collectively called the cyclic rotational shear tests, were conducted to investigate the deformation characteristics of the sand under continuous principal stress rotation conditions as well as the variation of the pore water pressure. However, in most of these cyclic rotational shear

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tests, the principal stress rotation is produced along a circular path on the plane. In this type of pure principal stress rotational tests, the amplitudes of the deviatoric and shear stresses are equal, but the direction of the principal stress rotates continuously. Yu et al.[11] investigated the influence of the pure principal stress rotation on the drained deformation behavior. They examined a number of factors affecting the cyclic response of sands such as the material density, the deviatoric stress level and the intermediate principal stress. Georgiannou and Konstadinou[12] conducted a series of the pure principal stress rotation tests to study the undrained response of Ottawa sand. Pan[13] performed the pure principal stress rotation tests on the saturated Nanjing fine sand with a relative density of 50%, to study the effects of the initial confining pressure, the initial stress ratio and the initial angle of the maximum principal stress direction on the dynamic strength. These experiments can be used to investigate the effects of the pure principal stress rotation on the characterisation of the soil behaviour, but they are of a limited use for studying the effects of the wave-induced principal stress rotation because the circular rotation stress path only occurs in a seabed of infinite thickness.

The seabed of infinite thickness is only an ideal case. Hsu and Jeng[14] developed a set of general solutions for the porous seabed of finite thickness. Their analytical solutions indicate that the thickness of the seabed plays a dominant role in the evaluation of the wave-induced response of the seabed. Later, the problem of the wave-induced dynamic response of the finite seabed has received much attention[15-22]. Meanwhile, laboratory experiments and field measurements of the wave-induced pore pressure and the effective stresses were also conducted on a porous soil of finite thickness. But the corresponding stress path for the seabed soil with finite thickness is not further examined, and there are not experimental evidences of its effects on the characterisation of the soil behaviour. Therefore, it is necessary to re-explore the work by Ishihara and Towhata[2] through theoretical and experimental investigations of a finite seabed.

The objective of this paper is to investigate the cyclic strength of the sand under the nonstandard elliptical rotation stress path induced by the wave loading. Before that, the nonstandard elliptical, i.e., non-circular, rotation stress path will be shown to be a more common state in the seabed soil of finite thickness due to the linear regular wave. And three parameters that determine the size and the shape of a nonstandard ellipse will be deduced. Then by using a hollow cylinder triaxial-torsional apparatus, the effects of the three parameters on the cyclic strength will be investigated separately and an experimental comparison between the circular stress path and the elliptical stress path will be made to demonstrate the necessity of adopting the elliptical rotation stress path for evaluating the cyclic strength of the sand in a finite seabed.

1. Nonstandard elliptical rotation stress path in the seabed

Considering the initial earth stress, the effective stress in the soil sediment can be expressed as

$$\bar{\sigma}_z' = -(\gamma_s - \gamma_w)z - \sigma_z', \quad \bar{\sigma}_x' = -(\gamma_s - \gamma_w)k_0 z - \sigma_x',$$

$$\bar{\tau}_{zx} = \tau_{zx} \tag{1}$$

where γ_s and γ_w are the unit weights of soil and water, respectively, and k_0 is the lateral earth pressure coefficient at rest. σ_z', σ_x' and τ_{zx} are the wave-induced effective stresses for 2-D progressive waves, as described by Hsu and Jeng[14]. z is the vertical position in the seabed.

The normal stress difference is expressed as

$$\frac{\bar{\sigma}_z' - \bar{\sigma}_x'}{2} = \frac{(\sigma_z' - \sigma_x')}{2} - D \tag{2}$$

where

$$D = \frac{1}{2}(1-k_0)(\gamma_s - \gamma_w)z \tag{3}$$

and

$$\frac{(\sigma_z' - \sigma_x')}{2} = \mathrm{Re}\{M_1 p_0 \mathrm{e}^{\mathrm{i}\varphi}\} \tag{4}$$

where $\mathrm{Re}\{\}$ indicates that only the real part of the complex solution is to be considered. $\mathrm{e}^{\mathrm{i}\varphi} = \cos\varphi + \mathrm{i}\sin\varphi$, where $\varphi = kx - \omega t$. k is the wave number, ω is the angular frequency of the wave, t is the time and x is the horizontal position. $p_0 = \gamma_w H / 2\cosh(kd)$ represents the amplitude of the wave loading on the surface. H is the wave height of the short-crested waves, and d is the water depth. M_1 can be deduced as follows based on the analytical solution of the dynamic response of the seabed under 2-D progressive waves by Hsu and Jeng[14]

$$M_1 = [C_1 + (kz-\lambda)C_2]\mathrm{e}^{kz} + [C_3 + (kz+\lambda)C_4]\mathrm{e}^{-kz} + \frac{k^2+\delta^2}{2}(C_5\mathrm{e}^{\delta z} + C_6\mathrm{e}^{-\delta z}) \tag{5}$$

The complex numbers C_1 through C_6 are six coefficients, and the parameter δ can be interpreted as the