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Full Length Article

Cyclic behavior of reinforced sand under principal stress rotation

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ABSTRACT

Although the cyclic rotation of the principal stress direction is important, its effect on the deformation behavior and dynamic properties of the reinforced soil has not been reported to date. Tests carried out on large-scale hollow cylinder samples reveal that the cyclic rotation of the principal stress direction results in significant variations of strain components (ε_z, ε_r, ε_θ and $\gamma_{z\theta}$) with periodic characteristics despite the deviatoric stress being constant during tests. This oscillation can be related to the corresponding variations in the stress components and the anisotropic fabric that rotate continuously along the principal stress direction. Sand under rotation appears to develop a plastic strain. Similar trends are observed for reinforced sand, but the shear interaction, the interlocking between particles and reinforcement layer, and the confinement result in significant reductions in the induced strains and associated irrecoverable plastic strains. Most of the strains occur in the first cycle, and as the number of cycles increases, the presence of strains becomes very small, which is almost insignificant. This indicates that the soil has reached anisotropic critical state (ACS), where a stable structure is formed after continuous orientation, realignment and rearrangement of the particles accompanied with increasing cyclic rotation. Rotation in the range of 60°–135° produces more induced strains even in the presence of the reinforcement, when compared with other ranges. This relates to the extension mode of the test in this range in which $\sigma_\theta > \sigma_z$ and to the relative approach between the mobilized plane and the weakest horizontal plane. Reinforcement results in an increase in shear modulus while it appears to have no effect on the damping ratio. Continuous cycles of rotation result in an increase in shear modulus and lower damping ratio due to the densification that causes a decrease in shear strain and less dissipation of energy.

1. Introduction

Reinforced soil is used widely in many geotechnical applications such as footings, embankment and pavement. In such applications, multiaxial loading and rotation in the principal stress direction are common features where the major principal stress direction is vertical for the soil element located along the load center. However, this direction rotates with α (from the vertical) when soil element is far from the centerline of the loading. Moreover, under many modes of loadings such as traffic loadings in road pavements or railways, the principal stress direction continuously rotates during moving wheel load (Ishihara and Towhata, 1983; Vaid et al., 1990; Wang et al., 2016).

It is essential to take the rotation of the principal stress direction into consideration when evaluating soil behavior, as it is found that changing not only the magnitude of the principal stress but also its direction has a significant effect on soil characteristics such as strength and deformation. This directional dependence is strongly linked to the inherent anisotropy exhibited by most soil types (Al-rkaby et al., 2016). For example, bearing capacity of footings can be reduced significantly as the principal stress direction rotates from a vertical direction (e.g. Meyerhof, 1978; Oda and Koishikawa, 1979; Azami et al., 2010). Moreover, the cyclic rotation of the principal stress direction results in significant variations of strain components, although deviatoric stress is constant during cyclic rotation (e.g. Vaid et al., 1990; Yang et al., 2007; Tong et al., 2010; Yu et al., 2016). There are many studies reported in the literature with the majority being conducted under undrained conditions (Ishihara and Towhata, 1983; Nakata et al., 1998; Yang et al., 2007) or under monotonic rotation of the principal stress direction (Symes et al., 1988; Wijewickreme and Vaid, 1993; Jiang et al., 2012; Cai et al., 2013). In addition, there are some studies performed to

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examine the cyclic rotation of the principal stress direction under drained conditions (e.g. Tong et al., 2010; Yu et al., 2016). However, all of these studies were limited to plain soil and did not investigate reinforced soil under cyclic rotation, despite the wide use of reinforced soil structure.

The hollow cylinder apparatus (HCA) was used to investigate soil characteristics under continuous cyclic rotation instead of the conventional triaxial test that could not simulate this condition. One reported study using plain sand found periodic variations in the induced strains due to the rotation of the principal stress direction and the majority of these strains were generated during the first cycle (Yu et al., 2016). These strains resulted in dilation and contractive volumetric strain during the rotation of the principal stress direction from 0° to 180°. However, at the end of each cycle, the total strain was contractive. Similar results were found by Xiong et al. (2016) using sand under the rotation of the principal stress direction resulting in plastic irrevocable strains. The shear strain reached its maximum value at $\alpha = 60^\circ$ and then decreased until $\alpha = 150^\circ$, while the axial strain induced in dilation side reached the maximum at $\alpha = 120^\circ$. Most of the induced volumetric strain took place in the first cycle and this strain varied significantly along α. With the subsequent cycles, it was generated at a low rate but the variation along α became insignificant due to the densification of soil (Tong et al., 2010; Xiong et al., 2016). These induced strains were also observed using a pure rotation test by Cai et al. (2013), although the intermediate principal stress ratio (b) was not constant along the rotation and only one cycle was considered.

The cyclic rotation under undrained conditions has a significant effect on soil behavior where flow deformation took place and more than 5% of pore pressure and strains were accumulated under constant deviatoric stress and b of 0.5 (Nakata et al., 1998). Similar trends were reported by Yang et al. (2007) under undrained conditions. Constant b and deviatoric stress increased the pore water pressure significantly due to cyclic rotation and most of it occurred during the first cycle. They observed that the generated pore pressures varied along α during the first cycle. However, in the subsequent cycles, the increasing rate tended to slow down and the variation along α became insignificant.

The dynamic characteristics of soil, such as the shear modulus and damping ratio, are of significant importance to analyze soil behavior and assess many geotechnical projects that involve a cyclic component (RaviShankar et al., 2005). These dynamic properties are affected by anisotropic fabric (Qin et al., 2015).

Few studies are reported in the literature regarding the dynamic properties of soil under cyclic rotation. Tong et al. (2008, 2010) found that the shear modulus increased as cyclic rotation continued.

Of the reported studies that did not consider the rotation of the principal stress direction, Naeini and Gholampoor (2014) examined the damping ratio for reinforced sand using a variety of numbers and places of geotextile under a normal cyclic test and found that the geotextile had no effect on the damping ratio. Moreover, in contrast to the findings of Tatsuoka et al. (1978), who suggested that there was no clear effect of void ratio on damping ratio, Kirar and Maheshwari (2013) demonstrated a decrease in the damping ratio and an increase in the shear modulus that are related to density increase. This is in agreement with Uthayakumar (1992) who concluded that a lower damping ratio, when the void ratio decreased, was associated with stiff material which dissipated lower amounts of energy during the cyclic loading.

It is apparent that the cyclic rotation has a very important effect on the deformation behavior of soil in many geotechnical problems, and should be considered in any design. Although reinforcement is widely used in many geotechnical applications to support the applied stress, the behavior of reinforced sand under cyclic rotation of the principal stress direction has not been reported in the literature to date. For this, experiments on large-size samples of geogrid-reinforced sand under cyclic rotation of the principal stress direction have been undertaken in this study. Additionally, the dynamic properties of reinforced sand under such conditions are investigated. This study is part of an ongoing research study at Curtin University and there are other aspects of this study yet to be investigated (Al-rkaby et al., 2017).

2. Materials and methods

2.1. Soil and geogrid

The sand used in this study was bought from Perth, Australia. It is classified as poorly graded sand (SP) and Table 1 shows some of its properties. Fig. 1 shows the particle size distribution of the sand used. High-density polyethylene geogrid was used for reinforcement and its properties are shown in Table 2.

2.2. Large hollow cylinder apparatus

The rotational cyclic tests were conducted using an advanced large HCA (HCA-600) at Curtin University. This apparatus can accommodate large samples with outer diameter $D_o = 300$ mm, inner diameter $D_i = 150$ mm and height $H = 600$ mm (Fig. 2). Despite the difficulties of handling such large samples, it can provide reliable and more accurate representation of soil deformations, especially under anisotropic conditions.

This device is useful for studying the anisotropic behavior of soil to consider different geotechnical problems that could not be simulated in a conventional triaxial apparatus, such as the effect of the rotation of the principal stress direction under a reasonably generalized stress state. Moreover, different directions of principal stress (α) or continuous rotation of the principal stress direction and various relative magnitudes of the intermediate principal stress ratio (b) can be achieved by the capability of independently controlling the axial load (W_z), torque (M_T), outer cell pressure (p_o), and inner cell pressure (p_i), resulting in individual control of the four stress components acting on an element (Fig. 2), i.e. vertical stress (σ_z), radial stress (σ_r), circumferential stress (σ_θ), and shear stress ($\tau_{z\theta}$).

2.3. Sample preparation

Sand was poured into samples and tamped as layers with a relative density of about 70%. Reinforcement geogrid with inner and outer diameters less than those of samples was placed in 2–5 layers at equal distance.

Table 1
Physical properties of the sand used.

Coefficient of uniformity	Coefficient of curvature	D_{30} (mm)	Medium grain size (mm)	D_{60} (mm)	Maximum void ratio	Minimum void ratio	Specific gravity	USCS classification	Friction angle (°)	Cohesion (kPa)
1.5	1.04	0.5	0.6	0.603	0.826	0.549	2.65	SP	40.1	0

Note: D_{30} and D_{60}: the sizes such that 30% and 60% of the particles are smaller than those sizes, respectively; USCS: unified soil classification system.