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The influence of undrained cyclic loading patterns and consolidation states on the deformation features of saturated fine sand over a wide strain range

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ABSTRACT

Undrained cyclic loading patterns and consolidation states can significantly affect the deformation features of medium-dense saturated fine-grained sand. A series of undrained cyclic loading tests with different consolidation states, i.e., various mean effective consolidation stresses (p_0), principal stress direction angles (α_0), ratios (R_0) of major and minor principal stresses, and relative magnitudes of intermediate principal stress (b_0), were performed on saturated micaceous fine sand specimens with a relative density of 50% corresponding to a wide strain range in the order of 10^{-5} to 10^{-2}. The patterns of cyclic axial, torsional, and axial–torsional combined loadings were applied in a hollow cylinder apparatus. The small-strain shear modulus G_0, the reference shear strain γ_r, curves for shear modulus reduction G/G_0, the damping ratio λ and Poisson's ratio υ with increasing strain were determined. The results of the cyclic axial–torsional combined tests showed a close relationship between G_0, γ_r, and υ as well as the consolidation state parameters p_0, R_0, α_0, and b_0. The G_0 and γ_r increased nearly linearly with increasing p_0 and with decreasing α_0 or b_0. The υ is strain dependent and increases as the p_0 decreases. Tests indicated that the reduction of G with increasing shear strain γ became more pronounced as p_0 increased. The relationship for the G/G_0 versus γ/γ_r was approximately independent of the cyclic loading patterns and the various values of parameters p_0, R_0, α_0, and b_0. A slight difference is noted between the damping ratios λ_t and λ_z, corresponding to vertical and torsional deformations. An empirical model was proposed for the dependence of the increase in damping ratio characteristics on the deviatoric strain.

1. Introduction

The required fundamental input parameters for seismic site response analysis include variation of the stiffness and material damping with the strain level information for each soil layer at the site in question. Ordinarily, these parameters would be based on laboratory specimen tests, either on the specific soils in question or on similar representative soils published in the literature. If the seismic site response is computed using equivalent linear analysis, the small strain shear modulus G_0 together with the normalized shear modulus reduction G/G_0 and damping ratio λ increase from small to large shear strains γ are required as key input parameters for each soil layer. Combined with the dynamic Poisson's ratio υ, these parameters are indispensable for seismic response analysis, and the parameterized empirical formulas might be beneficial for practical purposes in many cases.

Many researchers have investigated the small strain shear modulus G_0 values of sand and have proposed empirical type formulas for its prediction. For a given sand type, G_0 is primarily a function of the void ratio e and the mean effective consolidation stress p_0 (Seed and Idriss, 1970; Iwasaki and Tatsuoka, 1977; Kokusho, 1980; Menq, 2003; Wichtmann and Triantafyllidis, 2009; Cabalar, 2010; Senetakis et al., 2012).The G_0 increases with an exponent n_g of the mean effective consolidation stress p_0 (Salgado et al., 2000), but most researchers have proposed $n_g = 0.5$ for the value of the exponent. However, most empirical relationships proposed in the literature for estimation of the G_0 in granular soils predominately composed of quartz sands are not valid for volcanic soils (Senetakis et al., 2012). The existing study results in the literature indicate the important effect of the grain size distribution, often expressed in terms of the mean grain size d_{50} and the coefficient of uniformity c_u (Iwasaki and Tatsuoka, 1977; Ishihara, 1996; Menq, 2003; Hardin and Kalinski, 2005; Wichtmann and Triantafyllidis, 2009, 2010; Senetakis et al., 2012, 2013), on the G_0 of granular soils. Menq (2003) measured the G_0 values of 10 grain-size distribution curves for sand and found a slight increase in G_0 with an increasing mean grain size d_{50} for constant e and p_0, and the curves of $G_0(e)$ were steeper for the coarse material. In addition, Menq (2003) reported that G_0 increased with c_u for a constant relative density D_r. The test results of Hardin and Kalinski (2005) on sands and sand-gravel mixtures indicated that G_0 increased with increasing d_{50}. Wichtmann and Triantafyllidis (2009) measured the G_0 values of 25 different grain-size distribution curves of sand, and the

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results demonstrated that G_0 decreases significantly with increasing c_u for a constant e, whereas G_0 was not influenced by variations in the d_{50}. The G_0 was strongly affected by the grain size distribution curve for constant e, and G_0 decreased significantly with the increasing uniformity coefficient c_u (Iwasaki and Tatsuoka, 1977; Senetakis et al., 2012). It was clear that the overall effect of c_u on G_0 is fairly complex because of the additional effect of c_u on particle packing. Certain researchers noted that the effect of particle shape, often expressed in terms of the roundness R (Cho et al., 2006; Cabalar, 2010, 2015; Cabalar et al., 2013; Cabalar and Hasan, 2013), on the G_0 of granular soils, and higher roundness R values cause lower volumetric strain values. Other studies considered the significant influence of principal stress rotation and cross-anisotropy on the deformation and strength characteristics of soils (Arthur et al., 1980; Gutierrez et al., 1991; Lade et al., 2009), and focused on the effects of the morphology and mineralogy of the particle form, particularly on the cyclic properties of granular soils (Abbireddy et al., 2009; Clayton et al., 2009; Clayton, 2011; Senetakis et al., 2012; Senetakis and Madhusudhan, 2015). Nevertheless, the dynamic Poisson's ratio υ of sand is a matter that has attracted rather little attention thus far. However, the dynamic Poisson's ratio υ of sand significantly affects the seismic wave propagation characteristics in the soil. An approximate formula for υ was derived by Ishihara (1970, 1996) from the linear theory of a porous elastic medium, and υ decreases with increasing G_0 of the soils. Wichtmann and Triantafyllidis (2010) performed resonant column tests with additional P-wave measurements on 27 different grain-size distribution curves of sand. The results demonstrated that the υ at a notably small strain level did not depend on d_{50} but increased with increasing c_u and also tended to decrease with increasing p_0 for a constant c_u. These studies documented in the literature are noteworthy in understanding the change in G_0 and υ of sand as a function of selected dominant factors. In addition, the reference shear strain γ_r of granular soils is primarily a function of c_u and p_0 (Menq, 2003). However, Hardin and Kalinski (2005) demonstrated that γ_r increased with the square root of p_0 for isotropic consolidation.

Over the past 45 years, many researchers have extensively investigated the G/G_0 and λ versus γ relationships for sand via laboratory experiments, such as resonant column tests (Iwasaki and Tatsuoka, 1977; Li and Yang, 1998; Hardin and Kalinski, 2005; Wichtmann and Triantafyllidis, 2009; Cabalar, 2010; Senetakis et al., 2012, 2013, 2015; Senetakis and Madhusudhan, 2015), simple shear tests (Lanzo et al., 1997; Vucetic et al., 1998), cyclic triaxial tests (Seed and Idriss, 1970; Hardin and Drnevich, 1972; Kokusho, 1980; Seed et al., 1986; Kokusho and Tanaka, 1994; Rollins et al., 1998; Cabalar, 2010; El Mohtar et al., 2013), torsional shear tests (Guzman et al., 1989; Yasuda and Matsumoto, 1993; Chaudhary et al., 2002; Zhang et al., 2005), dynamic centrifuge tests (Brennan et al., 2005; Elgamal et al., 2005; Rayhani and El Naggar, 2008), and large-scale shake table tests (Chen et al., 2012). Studies with loading frequency control and number-of-cycle control in cyclic triaxial tests indicated that the change in G/G_0 and λ versus γ relationships is a function of p_0 and the number of loading cycles; G/G_0 and λ begin to change at a lower level of γ if p_0 is small, and increasing p_0 visibly shifts the G/G_0 curves upward and λ curves downward at the same shear strain. In particular, a general trend of a shift of the volumetric threshold shear strain to larger strains was observed for the volcanic saturated samples compared with the quartz sands, and this trend might play an important role in pore water pressure buildup assessment for granular soils (Senetakis et al., 2015). The existence of the threshold shear strain γ_{tv} was identified experimentally in pioneering studies (Silver and Seed, 1971; Dobry et al., 1982). Based on a synthesis of published laboratory data, Vucetic (1994) concluding that the particle bonds of soil should not be irreversibly disturbed and restructured with respect to each other at $\gamma < \gamma_{tv}$, developed a correlation between the trend of increasing γ_{tv} with increasing plasticity index PI for different soils. In other words, if γ is larger than γ_{tv}, G decreases, and excess pore water pressure accumulates relatively rapidly with the number of cycles in undrained conditions (Vucetic, 1994; Tabata, 2004). Furthermore, Tabata (2004) recommended the trend of increasing γ_{tv} with increasing PI instead of the trend proposed by Vucetic (1994). Recent studies revealed that c_u and d_{50} play important roles in the rate of modulus degradation and increase in damping (Menq, 2003; Senetakis et al., 2013; Wichtmann and Triantafyllidis, 2013). In addition, the experimental study by Senetakis et al. (2013) revealed that volcanic sands showed higher linearity compared with quartz sands and that this trend became more pronounced with decreasing p_0 and increasing c_u. These factors specify a state of the soil but not the state intrinsic to a soil. However, because of the limitations of the test equipment, previous studies have been confined mostly to either cyclic triaxial or cyclic torsional shear tests. In recent years, a new approach has been developed to evaluate the soil stress–strain histories using laboratory tests. These histories are used to estimate the variation of the soil modulus and material damping characteristics with the strain level. Chaudhary et al. (2002) performed a study of the effects of shearing direction on the shear modulus and damping ratio of medium dense Toyoura sand using a hollow cylinder apparatus (HCA). The G/G_0 and λ versus γ relationships were found to be minimally affected by the direction of the major principal stress. Centrifuge testing represents an alternative technique for investigation of soil behavior and avoids the limitations of the physical constraints of an element test. Elgamal et al. (2005) used centrifuge data to estimate the G/G_0 and λ versus γ relationships of saturated dense Nevada sand. Chen et al. (2012) investigated the shear modulus of saturated fine sand during the increasing and dissipating stages of excess pore water pressure (EPWP) using large-scale shake

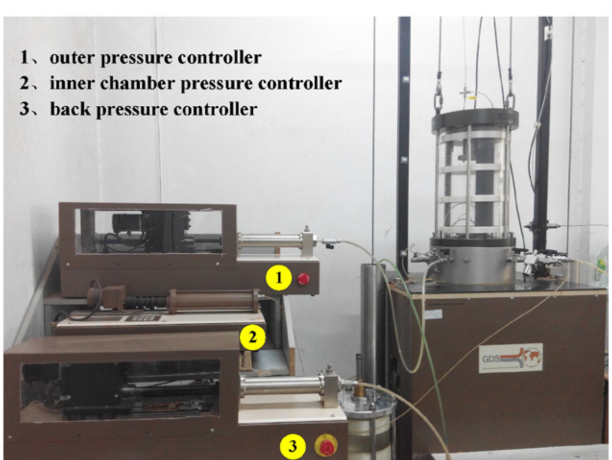

Fig. 1. GDS Hollow cylinder apparatus test system.

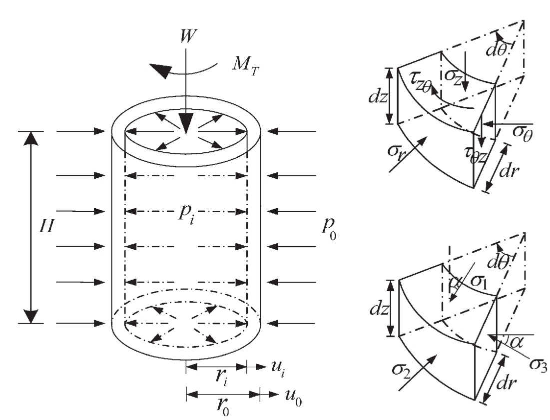

Fig. 2. Idealized stress and strain components within HCA subjected to axial and torsional loads.