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Cyclic Threshold Shear Strains of Sands Based on Pore Water Pressure Buildup and Variation of Deformation Characteristics

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The cyclic threshold shear strain γ_{th}^{c} is defined as the cyclic strain amplitude above which the pore water pressure in saturated sandy soil increases and/or the modulus and damping values vary with the number of loading cycles during cyclic loadings. In this paper, the cyclic threshold shear strains are thoroughly investigated on sands using torsional shear tests. Toyoura sand is tested at various densities, drainage conditions (dry, saturated drained, and saturated undrained), and effective confining pressures. Based on the test results, the cyclic threshold strains above which the excess pore water pressure increases and/or shear modulus and damping ratio vary with the number of cycles are determined. Cyclic hardening in dry and saturated drained conditions, and cyclic degradation in an undrained condition, are observed for the same sample, using identical testing equipment. γ_{th}^{c} for cyclic degradation is compared with γ_{th}^{c} for cyclic hardening. The variation of damping ratio with the number of cycles is observed at different drainage conditions, and γ_{th}^{c} for damping ratio is also investigated.

INTRODUCTION

Deformational characteristics of soil, expressed in terms of shear modulus G and material damping ratio D in shear and compression, are important parameters in the analysis and design of soil-structure systems subjected to cyclic and dynamic loadings such as earthquakes, waves, etc. Soil under cyclic loading shows different behavior depending on the cyclic shear strain amplitude γ_c at small ($\gamma_c < 10^{-3}\%$) to medium ($10^{-3}\% < \gamma_c < 10^{-1}\%$) shear strain. Dynamic deformation characteristics can be generally divided into 3 strain ranges:

- At small strains below the linear elastic threshold strain γ_{th}^{le}, soils exhibit linear quasi-elastic behavior, and G and D are practically constant independent of strain amplitude.
- Above the linear elastic threshold strain, soils behave nonlinearly.
- Above the cyclic threshold shear strain γ_{th}^{c}, G and D vary with the number of loading cycles N, which means that irrecoverable deformation occurs through the repetition of cyclic loadings and soil particle structure changes.

Also, in the case of undrained cyclic loadings above γ_{th}^{c}, excess pore water pressure is observed in soils due to the change of particle structure. Because the cyclic threshold shear strain is defined as the boundary above which deformation characteristics vary with the number of cycles, it is an important factor in liquefaction and site response analyses in the field of geotechnical earthquake engineering (Drnevich et al., 1970; Silver and Seed, 1971; Youd, 1972; Kim, 1991; Vucetic, 1994; Stokoe et al., 1994; and Ishihara, 1996).

Many researchers have published various results on the existence and characteristics of γ_{th}^{c}. Dobry et al. (1981, 1982) introduced the concept of γ_{th}^{c} for cyclic degradation in correlation with cyclic pore water pressure buildup. By performing cyclic undrained tests on saturated sands, Dobry and his co-workers (1981, 1982) concluded that γ_{th}^{c} is about 0.01% independent of relative density D_r and effective confining pressure σ_0'. Dyvik et al. (1984) investigated extensively the effects of effective confining pressure, relative density, the ratio of vertical to horizontal consolidation stress, overconsolidation ratio, prestraining and fabric. Utilizing a different approach, Kim (1991) performed resonant column and torsional shear tests on dry sand and defined γ_{th}^{c} for cyclic hardening based on the variation of G and D with the number of cycles. Kim found that γ_{th}^{c} defined from G is larger than that from D, and that both γ_{th}^{c}s increase with confining pressure. Vucetic (1994) identified the plasticity index PI as an important parameter, and he also found that γ_{th}^{c} increases with PI. Other researchers have observed that the cyclic threshold shear strain and γ_{th}^{c} on sands suggested by previous studies are distributed widely between $1.5 \times 10^{-3}\%$ and 0.04%, mostly near 0.01%, as tabulated in Table 1.

Most previous studies on the cyclic threshold shear strain focused on measurement of the increase of pore water pressure for cyclic degradation in the undrained condition. However, Kim (1991) observed cyclic hardening behaviour on dry sands, and he found the cyclic threshold shear strain by measuring the increase of shear modulus with the number of loading cycles. He showed that the values of γ_{th}^{c} are smaller than those determined by other studies based on pore water pressure measurement, and that γ_{th}^{c} increased with increased effective confining pressure. The values of γ_{th}^{c} obtained by pore water pressure are different from the values obtained by modulus variation. Further, the relations with γ_{th}^{c} for cyclic hardening and degradation are ambiguous, as they have been studied in conjunction with different samples and testing methods. Plus, study on γ_{th}^{c} for damping ratio has not been reported. Accordingly, γ_{th}^{c} for damping ratio, cyclic degradation and cyclic hardening require investigation.

In this paper, Toyoura sand is tested at various densities, drainage conditions (dry, saturated drained, and saturated undrained), and effective confining pressures using modified Stokoe-type torsional shear testing equipment to saturate specimens and perform tests in undrained conditions. Based on the test results, the cyclic threshold strains above which pore pressure increases and/or shear modulus and damping ratio vary with the number of cycles are determined. Cyclic hardening in the dry condition and

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