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Cyclic threshold shear strain in pore water pressure generation in clay in situ samples

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Abstract

The threshold level of the cyclic shear strain required for pore water pressure generation in clay samples is examined through the results of torsional hollow cylinder cyclic shearing tests according to JGS 0543-2009. The study confirms the previous results, namely, that the threshold cyclic shear strain is dependent on the effective consolidation stress and plasticity index ($I_{\rm p}$). The average and standard deviations in the estimated threshold strain levels are 0.038 ± 0.023% ($I_{\rm p} < 30$, $\sigma'_{\rm c} \leqq 100$ kN/m^2), 0.047 ± 0.016% ($I_{\rm p} < 30$, $\sigma'_{\rm c} > 100$ kN/m^2), 0.079 ± 0.028% ($30 \leqq I_{\rm p} < 5\ 0$), and 0.143 ± 0.041% ($I_{\rm p} \geqq 50$). As was found in past research, the levels of threshold strain for pore water pressure generation for clay are larger than those for clean sand. An increase in pore water pressure is only observed when the stiffness is reduced to around 80% of its initial value. This delay occurs because there is a difference between the cyclic threshold strain of the pore water pressure generation, $\gamma_{\rm tp}$, and the cyclic threshold strain of the stiffness degradation, $\gamma_{\rm td}$. Since the test procedure of JGS 0543-2009 is a standard scheme in the practical design process, it is expected that more data will become available in the near future which will allow for further discussions on threshold strain.

Keywords: Dynamic soil properties; Cyclic stiffness degradation; Damping ratio; Threshold strain; Pore water pressure generation (**IGC**:-D07)

1. Introduction

The strain dependency of soils is one of the most important characteristics considered in seismic designs. In particular, once the strain in a soil exceeds a certain level, defined as the threshold, the degradation of stiffness, an increase in the damping ratio, a change in the volume, and an increase in the pore water pressure are usually observed. The degradation of shear stiffness and an increase in the damping ratio with an increase in the shear strain level have been studied by many researchers (i.e., Anderson and Richart, 1976; Stokoe and Lodde, 1978; Kokusho et al., 1982; Ishibashi and Zhang, 1993). The threshold level of shear strain required to induce a volume change in soil or the generation of pore water pressure has also been investigated (i.e., Silver and Seed, 1971; Stoll and Kald, 1977; Dobry et al., 1982; Vucetic, 1994; Tabata and Vucetic, 2010). Hsu and Vucetic (2004) examined the volumetric cyclic threshold shear strain for cyclic settlement, $\gamma_{\rm tv}$, at different degrees of saturation with Norwegian Geotechnical Institute-type direct simple shear, multi-stage cyclic settlement tests, and showed that volumetric cyclic threshold shear strain $\gamma_{\rm tv}$ is larger for clays than for sands, and that it generally increases with the soil's plasticity index ($I_{\rm p}$). Hsu and Vucetic (2006) showed that the threshold shear strain for cyclic pore-water pressure $\gamma_{\rm tp}$ in cohesive soil is larger than that in cohesionless soil, and that it also increases with the soil's plasticity index ($I_{\rm p}$). Mortezaie

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and Vucetic (2016) examined the effect of effective consolidation stress on the threshold shear strain levels for cyclic degradation and cyclic pore water pressure generation in fully saturated clays. However, these studies on threshold shear strain were based on tests specially designed for the research. Thus, greater efforts should be made by the researchers to obtain further data. If discussions on threshold strain can be done with the test results in a practical design routine with in situ samples, more data and more detailed discussions will be possible in the near future.

From this viewpoint, a detailed examination of the threshold strain for pore water pressure generation in clay samples is conducted with test results using a practical test procedure. The procedure involves cyclic torsional shear tests on hollow cylinder specimens according to JGS 0543-2009. Although this test procedure for cyclic torsional shear tests is not used as often as that for cyclic triaxial tests according to JGS 0542-2009, it is also a standard procedure for obtaining dynamic soil characteristics for seismic response analyses.

In this study, a brief summary of the samples' properties is given in Section 2. Then, the data-processing procedure is explained in Section 3. A summary of the analysis is shown in Section 4, and a discussion follows in Section 5. Section 6 is the conclusion.

2. Test conditions and soil samples

The test results for 49 soil samples obtained in Japan were investigated. These samples were obtained from anonymous projects by the usual design procedure. In order to maintain anonymity, the authors regretfully cannot clarify the locations of the sampling sites. All samples were obtained by the standard tube sampler used in practice. The sampling was done according to the same process as that used in actual projects without giving any special consideration to improving the quality of the samples for research purposes. The quality of the obtained samples was examined by a comparison of the in situ shear wave velocity and the shear stiffness at a low strain level, as will be mentioned later. The sample preparation followed JGS 0102-2009 (JGS, 2015).

Cyclic torsional shear tests were conducted on hollow cylinder specimens using a multi-stage loading process to obtain the dynamic characteristics of the samples following the test procedure indicated in JGS0543-2009 (JGS, 2018). The test conditions were as follows:

- Saturated: B value $\geqq 0.95$
- Isotropically consolidated: consolidation stress of in situ condition.
  (Consolidation was confirmed by the 3t method, following Kamei et al., 1987.)
- Stress-controlled except for certain cases.
  (Nos. 01, 02, 03, and 21 were strain-controlled)
- Loading condition: sinusoidal loading of 0.1 Hz with 11 cycles in each stage.
- Undrained condition in cyclic loading, and drainage to fully dissipate pore water pressure at the end of each stage.
- Although it is not mandatory to record the pore water pressure in the process shown in JGS0543-2009, it was recorded in this study.

A summary of the samples is given in Table 1. Forty samples of alluvial clay (Ac), four samples of diluvial clay (Dc), and one sample of loam (Lm) were tested. Four samples were difficult to categorize. The characteristics of the samples spanned a wide range: 1.40–31.43 m in sampling depth, 0–18 in SPT N value, 1.357–1.958 g/cm^3 in wet density, 30.06–132.09% in natural water content, 0.0–54.0% in sand fraction, and 11.9–97.2 in plasticity index (I_p).

3. Data processing procedure for test results

The initial purpose of the cyclic torsional shear tests used in this study was to ascertain the dynamic characteristics of the samples. Therefore, the shear stiffness and the damping ratio in a multi-level loading stage were the main concern. However, pore water pressure generation is the focus of this study.

For both the stress-controlled and the strain-controlled tests, the test procedure consisted of using a multi-level loading stage. The values of shear strain, shear stiffness, damping ratio, and pore water pressure were obtained at the tenth cycle of loading. The data processing procedure for these values is summarized as follows.

3.1. Initial shear stiffness

In each stage of loading, focus is placed on the stress-strain relationship at the tenth loading cycle. The secant stiffness was obtained from the stress–strain relationship as shear stiffness G at the corresponding strain level. Initial stiffness G_0 (the stiffness at very small strain) was evaluated from the following process. First, the corresponding strain levels for shear stiffness G were plotted, as shown in Fig. 1 (a). Then, the plots were traced with a smooth line. No mathematical function was used for the trace line, but a hand-made line was used, as shown in Fig. 1(b). The extrapolated value on the trace line corresponding to the strain of 0.0001% was considered as initial stiffness G_0, as shown in Fig. 1(c).

Estimated initial stiffness G_0, from the above procedure, was compared with the stiffness calculated from the in situ shear wave velocity measurement. As shown in Fig. 2, these values agree well in general. Some cases (Nos. 05, 21, and 44), with large in situ shear wave velocities, showed large differences in estimated initial stiffness G_0. The samples were taken from a diluvial clay layer (Dc), and the difference may have been caused by a disturbance during the sampling.

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