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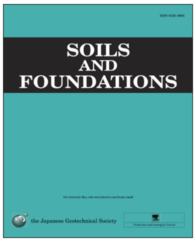

Prediction of pore water pressure generation leading to liquefaction under torsional cyclic loading

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Abstract

Undrained cyclic loading tests were performed under torsional shear in a hollow cylindrical apparatus on four sands of various densities, initial stress levels, gradings and origins to establish the pattern of excess pore water pressure generation with cycles leading to initial liquefaction. Two equations were derived to predict this pattern. The first is based on the method introduced by Ishibashi et al. (1977) and incorporates density and the effective stress level into the original equation. The second involves a unique relationship between the excess pore water pressure and the shear work imparted to the sand and it was obtained independent of the shear stress amplitude when the dissipated shear work was normalized with respect to density and the effective stress level. The excess pore water pressure required to induce liquefaction was found to necessitate lower normalized shear work from finer sands. These equations can be used to assess the liquefaction potential and/or can be directly related to the amount of seismic energy dissipated in the field.

Keywords: Laboratory test; Torsional loading; Sand; Pore water pressure; Liquefaction; Energy; Earthquake

1. Introduction

The liquefaction of granular deposits has been a major cause of damage to engineering structures during earthquakes; and hence, the assessment of the liquefaction potential has received considerable attention. To evaluate the liquefaction potential, the amplitude of shear stress or strain has traditionally been related to the number of cycles to liquefaction (Seed and Idriss, 1971; Dobry et al., 1982). Since the build-up of pore water pressure during undrained cyclic loading is the underlying mechanism that leads to liquefaction, a number of methods to predict the pore water pressure have been derived based on results obtained from cyclic tests (Seed and Booker, 1977; Chang et al., 1981; Mitchell and Dubin, 1986).

The standout pore pressure prediction model, presented by Ishibashi et al. (1977), was established as one of the most commonly used models (Krishnaswamy and Isaac, 1995; Uchida and Stedman, 2003; Georgiannou and Tsomokos, 2008). Ishibashi et al. (1977) obtained an equation that predicts the values for the rise in incremental pore pressure as a function of the stress history, the number of cycles and the applied shear stress. Note that density and stress level were not considered as variables, and that the four constants included in the equation are material-dependent. Sherif et al. (1978) and Ishibashi et al. (1982) re-evaluated the values for the four constants to account for the variations in density, mean grain size, the coefficient of sand uniformity and angularity.

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During the last two decades, the generation of pore water pressure was related to the amount of dissipated energy during cyclic loading, eventually leading to liquefaction in the laboratory, instead of the number of cycles to liquefaction, following the energy-based method introduced by Nemat-Nasser and Shokooh (1979). Efforts were focused on obtaining the energy at the onset of liquefaction in the laboratory so that it could be directly related to the amount of seismic energy dissipated in the soil (Berrill and Davis, 1985; Law et al., 1990; Figueroa et al., 1994; Liang et al., 1995; Dief and Figueroa, 2007).

Torsional shear testing is known for its ability to simulate the field conditions during earthquake/cyclic loading more realistically, as cyclic shear stress is applied to the horizontal plane of the soil specimen. In this respect, the limitations of the triaxial apparatus, apart from the jump rotation of the major principal stress it introduces upon stress reversal, have been widely acknowledged. On the other hand, given the uncertainties of the stress state in a simple shear device, a hollow cylindrical torsional shear apparatus has been used to simulate the simple shear stress and deformation conditions. Moreover, it allows for the rotation of the major principal stress in varying amounts about the vertical direction in concurrence with the increasing shear stress to simulate the in situ loading conditions (Georgiannou and Konstadinou, 2014a) and the application of initial static shear to represent the sloping ground conditions (Chiaro et al., 2012, 2013).

In this study, following the procedure presented by Ishibashi et al. (1977), an empirical equation is presented to predict the accumulation of pore water pressure up to the initial liquefaction during undrained torsional loading in a hollow cylindrical apparatus. Density and the effective stress level, parameters widely known to affect the liquefaction potential, have been incorporated into the foregoing equation as variables; as a consequence, a single constant reflecting the material properties has replaced the original four material constants. Moreover, the development of pore water pressure up to the initial liquefaction has been expressed as a function of the dissipated energy, and an expression was derived including density, stress level and mean grain size as the variables. The expression yields a unique pore pressure–energy curve for each of the four sands in the experimental database.

From a practical viewpoint, the proposed equations can be readily implemented in numerical calculations related to liquefaction problems due to their simplicity. Predicting the generation of pore water pressure during torsional cyclic loading, for sands of various densities, initial stress levels, gradings and origins, provides a level of confidence for their use in numerical models for liquefaction potential.

2. Materials and testing methods

The materials employed in this study were four silica sands, namely, Ham River Sand (HRS), Fontainebleau sand, M31 sand and Ottawa sand. The physical properties of these sands are given in Table 1, while their grain-size distribution curves are presented in Fig. 1. Apart from the grading, the shape of the sand particles emerges as a significant parameter altering the response of sands of similar grading in a remarkable manner. The materials tested here represent a range in gradings, typical of research sands, while HRS and M31 have the same grading, but different particle shapes, namely, subangular and rounded, respectively. All specimens were formed by pluviation through water (Hight et al., 1983; Vaid and Negussey, 1988), a method that produces specimens that can simulate naturally deposited sands (Oda et al., 1978; Miura and Toki, 1984). The split mold, falling from a constant height, is filled with soil. The relative density values of the majority of the specimens, after consolidation and prior to shearing, were D_r=35 ± 3%, 43 ± 3%, 40 ± 3% and 26 ± 5% for HRS, Fontainebleau, M31 and Ottawa sand, respectively. Looser specimens were obtained by changing the raining height of the sand grains, while denser specimens were obtained by tapping the mold after the sand had settled through the water. After confirming saturation, with B values in excess of 0.97, the specimens were isotropically consolidated, and after an ageing period of 3 h, they were subjected to constant stress amplitude cyclic loading under undrained torsional shear conditions.

Table 1
Properties of the tested sands.

	Fontainebleau	HRS	M31	Ottawa
G_s	2.64	2.66	2.65	2.65
e_{min}	0.54	0.526	0.528	0.502
e_{max}	0.865	0.87	0.87	0.742
Mean grain size, d_{50}	0.22	0.32	0.29	0.72
Coefficient of uniformity, C_u	1.55	1.71	1.59	1.36

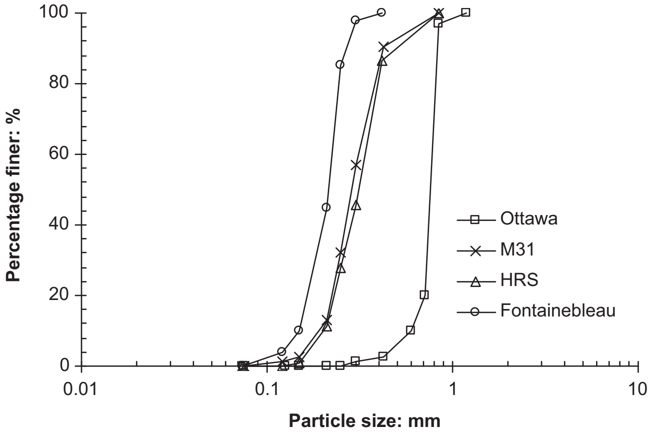

Fig. 1. Grain-size distribution curves.

To account for the effect of density, testing was carried out on specimens isotropically consolidated at constant mean effective stress of $p_i' = \sigma_1' + \sigma_2' + \sigma_3'/3$=130 kPa over a range of densities D_r=30–60% for the case of HRS and Fontainebleau sands. To account for the effect of the consolidation stress level, testing was carried out for a range in initial mean effective stress levels (p_i'=100–320 kPa) for the case of M31 and Ottawa sands at D_r~40% and 26%, respectively. Table 2