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Energy evaluation for liquefaction-induced strain of loose sands by harmonic and irregular loading tests

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ABSTRACT

A series of stress-controlled undrained cyclic loading tests using a torsional simple shear apparatus are carried out on reconstituted loose sand specimens by applying harmonic and irregular shear stresses to evaluate cumulative dissipated and strain energies, $\Sigma\Delta W$ and ΣW, for liquefaction-induced strain before and after 100% pore-pressure buildup. The tests with harmonic stresses show that the energy $\Sigma\Delta W$, which is roughly proportional to effective confining stress, is uniquely correlated with induced strains irrespective of cyclic stress amplitudes and number of cycles for liquefaction. Also found is that an almost unique correlation holds between $\Sigma\Delta W$ and ΣW for all the harmonic loading tests. The tests with irregular stresses also indicate an almost unique correlation of energy with induced strains up to initial liquefaction, however the wave irregularity makes the correlation more dispersive and wave-dependent for larger strains, though the induced strain may still be evaluated using the energy-dependent correlation within some uncertainty allowable for engineering purposes.

1. Introduction

The energy-based liquefaction evaluation method (EBM) was first proposed by Davis and Berrill [1] following theoretical research by Nemat-Nasser and Shokooh [2] that pore-pressure buildup is directly related to the amount of dissipated energy during cyclic loading in soil. After that, Towhata and Ishihara [3] conducted undrained cyclic loading tests using a hollow cylindrical torsional shear apparatus focusing on the dissipated energy in soil specimens in which a unique relationship was found between shear work (cumulative dissipated energy) and excess pore-pressure independent of shear stress history. Yanagisawa and Sugano [4] conducted similar strain-controlled cyclic shear tests by harmonic and additional irregular loading on the effect of seismic strain history on the shear work versus pore-pressure relationship. Laboratory soil test conducted by Figueroa et al. [5] using a strain-controlled torsional shear device also demonstrated that the cumulative dissipated energy was closely connected to pore-pressure buildup under different confining stresses. More recently, Azeiteiro et al. [6] carried out cyclic triaxial tests to evaluate the effect of the location and magnitude of the largest peak of earthquake-induced stress, and found that a unique relationship exists between the dissipated energy and the pressure buildup ratio. Thus, there are quite a few preceding research on dissipated energy for liquefaction, though the pore-pressure ratio was focused in most of them as a key parameter to correlate with the energy.

Apart from these researches mainly concerned with pressure-buildup, Kazama et al. [7] carried out constant strain-controlled cyclic triaxial tests to focus on energy-dissipation capacity obtained from stress-strain loops even after 100% pressure-buildup to consider ductility of various soils to be considered in design. Kokusho [8] revisited a series of cyclic triaxial liquefaction test results by harmonic loading and found that the cumulative dissipated energy is correlated well with not only pore-pressure buildup but also induced strain, and with cumulative strain energy measured in the same test as well. The same author also found that a unique energy-strain correlation holds not only up to 100% pore-pressure buildup (initial liquefaction) but also after that to measure the severity of liquefaction.

In this research, a series of stress-controlled undrained cyclic torsional simple shear tests are conducted focusing on the liquefaction-induced strain on reconstituted loose to medium density sands of relative density $D_r \approx$ 30–50% without and with non-plastic fines. Harmonic and irregular cyclic stresses are given to the specimens, wherein not only the excess pore-pressure but also the induced strain is correlated with the dissipated energy. In addition to the above-mentioned research on energy capacity, the strain energy given to the same specimens during liquefaction process is also measured for energy demand to be employed in the energy-based liquefaction evaluation method by Kokusho [8]. Effects of cyclic stress ratio, number of cycles and wave irregularity on the uniqueness of energy-dependent strain evaluation are particularly focused.

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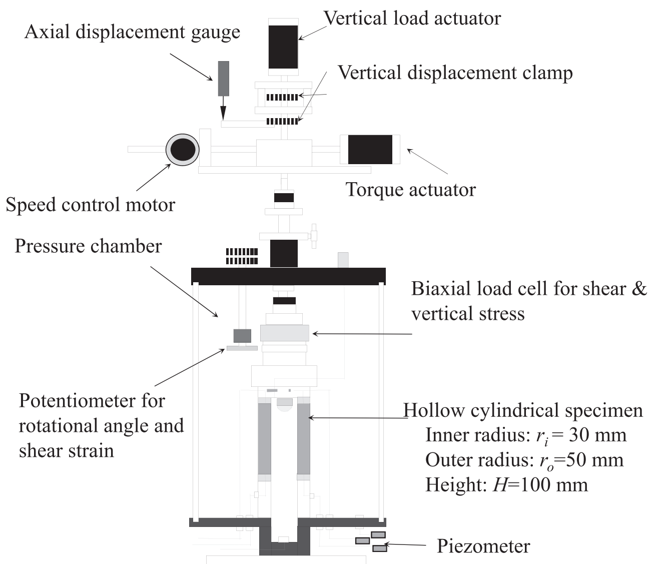


Fig. 1. Hollow cylinder torsional shear test apparatus.

2. Test method and data reduction

Fig. 1 illustrates the hollow cylinder torsional shear test apparatus used, where the specimen size is r_i = 30 mm and r_o = 50 mm in inner and outer radius, respectively, and H = 100 mm in height. Futtsu beach sand (along the Tokyo bay), non-weathered sub-round particles with the mean grain size D_{50} = 0.19 mm and the uniformity coefficient C_u = 1.9 was used. Non-plastic fines made from rock flour were added in some tests parametrically changing fines content F_c from 0% to 30% to reproduce fines-containing sands wherein soil skeleton initially "sand grain-supporting" is approaching to "fine matrix-supporting" with increasing F_c. The grain-size curves and associated physical properties are depicted in Fig. 2(a) and (b) for the original clean sand and those mixed with fines as well as the pure fines. It is postulated here that the maximum and minimum void ratios in Fig. 2(b) can serve as a common scale to determine relative density of granular materials for sands with $F_c \lesssim$ 30% wherein the soil skeleton is essentially sand grain-supporting rather than fine-matrix supporting. All the test specimens were prepared by the moist tamping method to target relative densities, D_r = 30% and 50%. Thus, relatively loose sand was chosen as the research target here because in case histories severe liquefaction damage (e.g. in Niigata city during the 1964 Niigata earthquake and in Kobe city during the 1995 Kobe earthquake) occurred mostly in loose sandy soils with relative density lower than 40–50% or normalized SPT N_1-value lower than 6–10.

The specimens were saturated with de-aired water and isotropically consolidated by effective confining stress σ'_c = 98 kPa in most cases, or 48 or 196 kPa in some cases, with back pressure of 196 kPa [9]. Then, the specimen was cyclically loaded in the undrained condition by torsional shear stress τ_d. The cyclic stress τ_d was either harmonic motion of frequency 0.1 Hz or irregular seismic motion with its time scale elongated by 10 times. During the test, vertical and torque loads were monitored by a biaxial load transducer shown in Fig. 1 inside the pressure cell to avoid frictional effects on the measurements. The cyclic shear stress τ_d was applied on the specimen top, which was assumed to be constantly distributed over the specimen and calculated from the torque T measured by the biaxial load cell as:

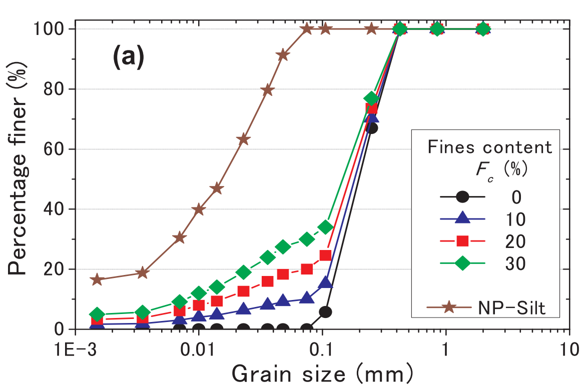
$$\tau_d = \frac{3T}{2\pi (r_o^3 - r_i^3)} \tag{1}$$

The torsional angle θ of the specimen cap was measured by a rotational angle transducer (potentiometer) inside the pressure chamber, and the shear strain of specimen was determined at the center of the specimen thickness $(r_i + r_o)/2$ from θ and the specimen height H as:

$$\gamma = \frac{r_i + r_o}{2H}\theta \tag{2}$$

Axial displacement of the specimen was also monitored by LVDT outside the pressure cell to calculate induced vertical strain during torsional cyclic loading.

Fig. 3 exemplifies typical time histories of (a) cyclic shear stress τ_d, (b) excess pore-pressure normalized by effective confining stress $\Delta u/\sigma'_c$, (c) shear strain γ, (d) normalized cumulative dissipated energy $\sum \Delta W/\sigma'_c$, (e) axial stress σ_a, and (f) axial strain ε_a obtained for clean sand of D_r = 45% and F_c = 0% by the cyclic stress ratios $CSR = \tau_d/\sigma_c'$ = 0.236 for effective confining stress σ_c' = 98 kPa. Initial liquefaction for $\Delta u/\sigma'_c$ = 1.0 and double-amplitude shear strain γ_{DA} = 7.5% occurs at the number of loading cycles for initial liquefaction $N_L \equiv N_c$ = 12.7 in this case. Around there, the energy $\sum \Delta W/\sigma'_c$ also starts to increase with higher gradient. It is also observed that the axial



(b)

F_c (%)	ρ_s (g/cm^3)	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	e_{max}	e_{min}
0	2.741	1.632	1.316	1.083	0.680
5	2.739	1.717	1.323	1.070	0.595
10	2.742	1.777	1.302	1.106	0.543
20	2.739	1.886	1.261	1.172	0.452
30	2.729	1.902	1.171	1.330	0.435

Fig. 2. Grain-size curves (a) and physical properties (b) for Futtsu sand with variable fines contents.

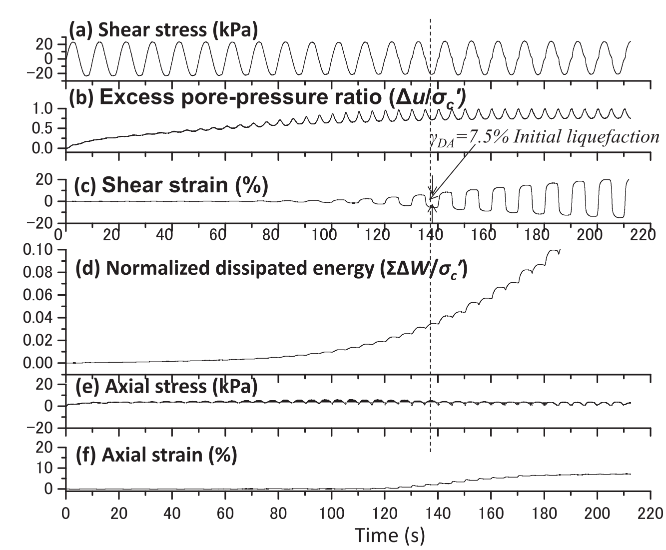


Fig. 3. Typical time histories of (a) cyclic shear stress, (b) normalized excess pore-pressure, (c) shear strain, (d) normalized cumulative dissipated energy, (e) axial stress, and (f) axial strain. (D_r = 45%, F_c = 0%, CSR = 0.236, $\Delta u/\sigma_c'$ = 98 kPa).