An Undrained Cyclic Torsional Shear Test on Sand Boil with Several Densities

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1. Introduction

A sequence of two strike-slip earthquakes occurred on 14th and 16th April 2016 in the intraplate region of Kyushu island, Japan, apart from the subduction zones, and caused significant harm and disruption to the Kumamoto region in the Kyushu island. The magnitude of foreshock was 6.5 and the maximum magnitude was 7.3. This series of major earthquakes caused great damages to the island of Kyushu. The phenomenon of liquefaction occurred in few districts of Kumamoto city. In residential areas, the phenomenon of sand blast and building inclination caused by liquefaction were obvious. Therefore, in order to study the physical properties and liquefaction characteristics, the sand boil was collected from Kumamoto city and a series of tests were performed. Fig.1 shows the sand boil from the 2016 Kumamoto Earthquake next to the door.

Fig.1 Sand boil of Kumamoto earthquake

2. Test material and experimental procedure

The sand boil which was used for the test was collected from Chikami district in Kumamoto city, and Toyoura sand was used as a comparison. Toyoura sand has been widely used for laboratory liquefaction studies in Japan. Fig.2 shows the grain size distribution curve and table 1 shows the physical properties of sand boil and Toyoura sand. The minimum and maximum density tests (JGS0161) were carried out. As shown in Fig.2, most sand particles in the sand boil are between 0.1-0.6mm. The density of sand boil is 2.671g/cm^3 which is larger than that of Toyoura sand. According to the grain size analysis, it was found that there was almost no difference in grain size. One possibility is because the collected sand was sprayed out from the same well at the same time. Furthermore, the liquefied sand was not classified, and directly sprayed out from the ground surface. Both liquid limit and plastic limit are Non-Plastic (NP). When making samples, the relative density were 26%, 46% and 60%. Corresponding to the relative density, the numbers of hits were 50, 70 and 120 respectively. The hollow cylindrical specimen was 10cm in outer diameter, 6cm in inner diameter and 10cm in height. A cyclic torsional shear test equipment was used and the sample preparation method was water pluviation method. In the sample preparation, the material was used under the condition of natural water content without drying treatment. After making the specimen, the deaired water was percolated from the bottom of specimen. When the pore pressure coefficient B is over 0.95, it can be considered that the specimen was saturated. The specimen was then isotropically consolidated under the initial effective confining pressure σ_0'=98kPa. After consolidation, the specimen was subjected to cyclic shear stress under undrained condition. The input waveform was sinusoidal with a frequency of 0.1Hz. When the double-amplitude shear strain reaches DA=7.5%, it was estimated that liquefaction occurred. After 20 cyclic loadings, the monotonic static loading test was carried out under undrained condition. The static loading test was conducted under strain controlled condition.

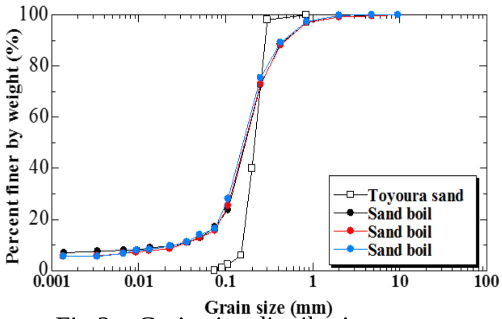

Fig.2 Grain size distribution curve

Table 1 Physical properties

	Toyoura sand	Sand boil
$\rho_s(g/cm^3)$	2.645	2.671
e_{max}	0.981	1.258
e_{min}	0.608	0.687
w_L	NP	NP
w_P	NP	NP

3. Liquefaction strength properties

R and N_c stand for the cyclic stress ratio and the number of cycles to attain DA=7.5% respectively. The relationship between R and N_c is shown in Fig.3. The values of liquefaction strength ratio R_{L20} (when N_c=20) are shown in table 2. In Fig.3, The four curves of different colors represent the properties of four kinds of D_r. The black line expresses the liquefaction strength curve of Toyoura sand, while the other lines represent the liquefaction strength curve of sand boil. As shown in the figure, R decreases with the increase of N_c in accordance with the slopes of the curves. All the curves slope gently with the increase of N_c. According to this data, it is obvious that the R_{L20} at D_r =63% is larger than those at both D_r =46% and D_r =26%. Comparing with R_{L20} of 26%, R_{L20} of 46% is larger. It is because the mass of specimens are different. When the sizes of specimens are same, the larger the mass, the greater the D_r will be. As 0.293>0.220>0.190, R_{L20} increases with the increase of D_r when the experimental material is sand boil. According to these curves, R_{L20} of sand boil is larger than that of Toyoura sand. One possibility is that although the sand boil is Non-Plastic, it is more cohesive due to the fines.

4. Deformation properties from a liquefaction experiment

The relationships between shear stress and shear strain obtained by the static loading test after undrained cyclic loading test is shown in Figs.4 and 5. F_L is the safety factor against liquefaction which is defined by the ratio of the cyclic stress ratio R and liquefaction strength ratio R_{L20}. The static curves represent the relationship between stress and strain obtained by the static test without cyclic loading. The other curves were obtained by the static test with cyclic loading. After liquefaction, the strain before the recovery of the shear modulus is called as the reference strain at resistance transformation, γ_L, and the slope of the region is called as shear modulus G_1. The slope of recovery region starting from the resistance inflection point is called as G_2. Both G_1 and G_2 are also defined as the ratio of shear stress to the shear strain. G_2 is proportional to F_L when D_r are the same. It can be seen from Fig.4 that the shear moduli were lost after liquefaction. According to Fig.4, the larger the D_r is, the greater the G_1 and G_2 will be. It is because the mass has an influence on the shear modulus. G_1, G_2 and D_r increase with the increase of mass. When D_r is over 60%, the curves at F_L=0.99 and F_L=0.80 coincide. According to Fig.5, G_1 of Toyoura sand is close to zero and it is also smaller than that of sand boil when their safety factors are same. However, G_2 is the opposite of G_1. G_2 of Toyoura sand is larger than that of sand boil.

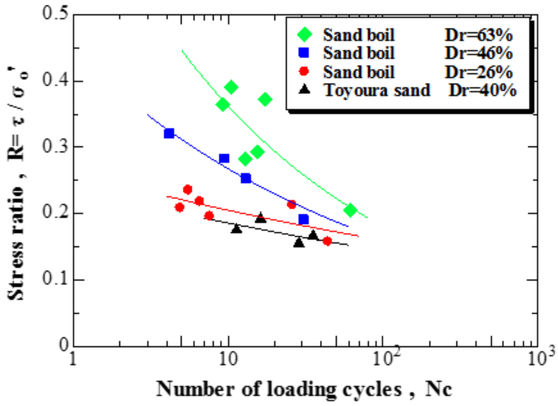

Fig.3 Relationship between R and N_c

Table 2 Liquefaction ratio R_{L20}

	Sand boil (Dr=26%)	Sand boil (D_r =46%)	Sand boil (D_r =63%)
R_{L20}	0.190	0.220	0.291

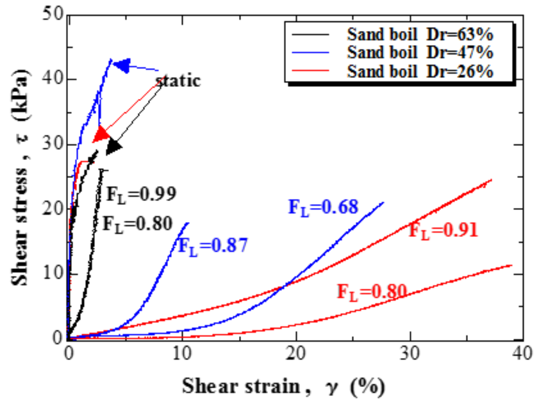

Fig.4 Relationship between τ and γ

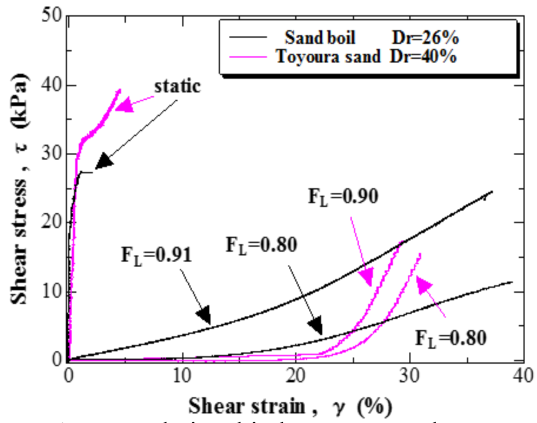

Fig.5 Relationship between τ and γ

5. Conclusions

1) R_{L20} increases with the increase of D_r when the experimental material is sand boil. All the curves slope gently with the increase of N_c. R_{L20} of sand boil is larger than that of Toyoura sand.

2) From the results of static loading test on sand boil, G_2 is proportional to F_L. D_r, G_1 and G_2 increase with the increase of mass. G_1 of Toyoura sand is smaller than that of sand boil when their safety factors are the same. G_2 of Toyoura sand is larger than that of sand boil.