An Undrained Cyclic Torsional Shear Test on Sand Boil Retrieved after the 2016 Kumamoto Earthquake

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1. Introduction

The 2016 Kumamoto Earthquakes were a series of earthquakes, including a mainshock earthquake with a magnitude 7.0 at a depth of about 10 kilometers and a foreshock earthquake with a magnitude 6.2 at a depth of about 11 kilometers. The series of major earthquakes inflicted major damage to a wide area of the island of Kyushu. The phenomenon of liquefaction happened in the earthquake. In residential areas, the phenomenon of sand blast, building inclination were obvious. It is so essential to study and analyse the ground after the liquefaction phenomenon. Therefore, in order to study the physical properties and liquefaction characteristics, a series of undrained cyclic torsional shear tests were performed on the collected sand boil. Photo 1 shows the sand boil from the 2016 Kumamoto Earthquake next to the wall.

Photo 1 Sand boil of Kumamoto Earthquake

2. Test material and experimental program

The test materials include sand boil and Toyoura sand. 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. Fig.1 shows the grain size distribution curve and table 1 shows the physical properties. The minimum and maximum density test (JGS0161) was carried out. In the test criterion, less than 5% of the dry weight percentage of the sand sample passed through a 75-μm sieve and the remaining sand was over 95%. In this test, the fine fraction content F_c is 16%. Three points were selected randomly from the collected material, and the grain size analysis was conducted. It was found that there was just a little 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 wasn't classified, and directly sprayed out from the ground surface. Both liquid limit and plastic limit are non-plastic (NP). The hollow cylindrical specimen was 10cm in the outer diameter, 6cm in the inner diameter and 10cm in the height. A cyclic torsional shear test equipment was used. 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 the making of 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 the 20 times cyclic loadings, the monotonic static loading test was carried out under undrained condition. The static loading test was conducted under strain controlled condition. The load speed was γ=5%/min.

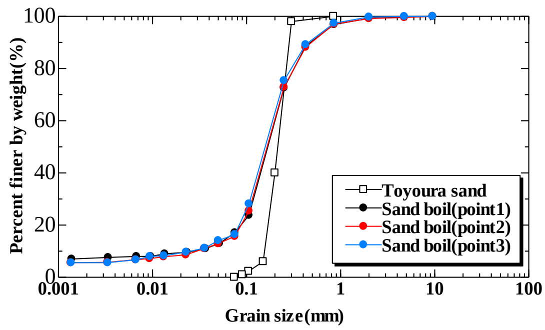

Fig.1 Grain size distribution

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 of sand boil in the Kumamoto Earthquake

The relationship between the cyclic stress ratio, R, and the number of cycles to attain DA=7.5%, N_c, is shown in Fig.2. The liquefaction strength ratio R_{L20} (when N_c=20) is shown in table 2. In Fig.2, the red line expresses the liquefaction strength curve of sand boil (D_r =26%), while the black line expresses the liquefaction strength curve of Toyoura sand. According to these results, R_{L20} of sand boil is a little larger than that of Toyoura sand. The reason is that although it is non-plastic, it is more cohesive due to the fines. Both the blue and red lines express the liquefaction strength curve of sand boils with D_r =26% and 46%. According to this data, it is obvious that the R_{L20} at D_r =46% is larger than that at D_r =26%. This result shows that R_{L20} increases with the increase of D_r when the experimental material is sand boil.

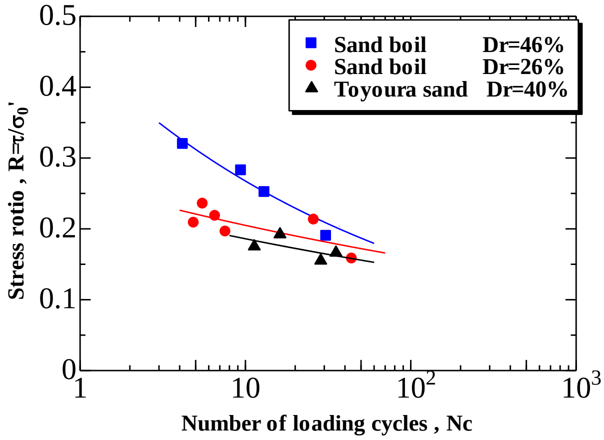

Fig.2 The relationship between R and N_c

Table 2 Liquefaction ratio R_{L20}

	Toyoura sand (Dr=40%)	Sand boil (D_r =26%)	Sand boil (D_r =46%)
R_{L20}	0.172	0.190	0.220

4. Deformation properties from a liquefaction experiment

In the Kumamoto Earthquake, the relationships between shear stress and shear strain obtained by the static loading test after undrained cyclic loading test is shown in Figs.3 and 4. In the result of the static loading test, the safety factor against liquefaction, F_L was defined by the ratio of the cyclic stress ratio R and liquefaction strength ratio R_{L20}. Static curve expresses the relationship between stress and strain obtained by the static test without 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. Table 3 shows the values of G_1 and F_L in the tests on the sand boil and Toyoura sand. It can be seen from Figs.3 and 4 that the shear moduli were lost after liquefaction. According to black lines of these two figures, comparing G_1 in Fig.3 with G_1 in Fig.4, the G_1 in Fig.3 is larger. Particularly, when F_L is around 0.9, the difference is obvious. In the case of sand boil, the shear modulus is not close to zero, but it is still a relatively small value. The red lines and black lines in Fig.3 indicate that G_1 at D_r =46% is larger than that at D_r =26%, but F_L at D_r =46% is less than that at D_r =26%. The reason for this is due to the shear modulus at D_r =46% which is larger than that at D_r =26%.

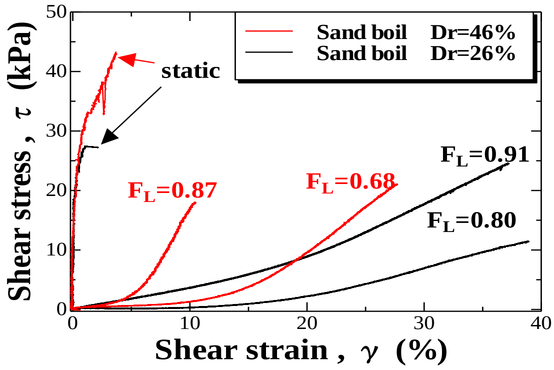

Fig.3 The relationship between τ and γ

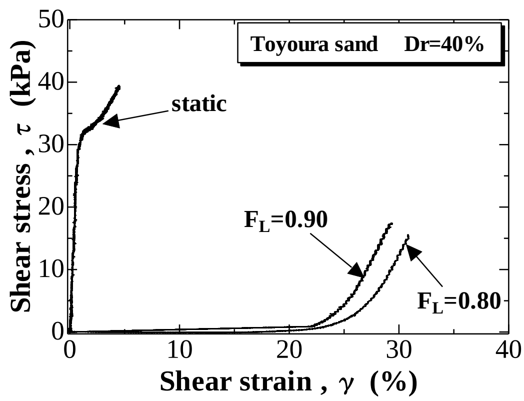

Fig.4 The relationship between τ and γ

5. Conclusions

1) The liquefaction strength R_{L20} of sand boil is larger than that of Toyoura sand, but the difference is not large. R_{L20} increases with the increase of D_r when the experimental material is sand boil.

2) After liquefaction, the shear modulus G_1 of sand boil with D_r =26% is larger than that of Toyoura sand. When the safety factor against liquefaction F_L is relatively high, such as F_L =0.9, the difference becomes obvious. The shear modulus of D_r =46% is larger than that of D_r =26% when both materials are sand boil.

Table 3 Shear modulus G_1

	Toyoura sand (D_r =40%)		Sand boil (D_r =26%)		Sand boil (D_r =46%)	
F_L	0.80	0.90	0.80	0.91	0.68	0.87
G_1 (kPa)	2.69	4.42	3.50	36.9	10.8	37.3