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Cyclic Torsional Shear Tests to Evaluate the Effect of Long Shaking during the 2011 Great East Japan Earthquake on Liquefaction Strength

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ABSTRACT

The 2011 Great East Japan Earthquake, having a magnitude of Mw = 9.0, struck on March 11, 2011. This earthquake was a trench earthquake with extremely long duration. Conversely, the 1995 Hyogoken Nambu Earthquake with a magnitude of Mw = 7.3 (Japan Meteorological Agency, 2001), which occurred at the Rokko and the Nojima faults, was a near-field earthquake of shorter duration. In this study the authors conduct cyclic torsional shear tests to evaluate the effect of earthquake duration on liquefaction strength. Three types of shear waves were applied to specimens: one was a seismic wave like that which was recorded during the main shock of the 2011 Great East Japan Earthquake and the others were like those that were recorded during the main shock of the 1995 Hyogoken Nambu Earthquake. Test results show that the liquefaction strength ratio due to the Great East Japan Earthquake was smaller than that due to the Hyogoken Nambu Earthquake.

Introduction

The Great East Japan Earthquake occurred on March 11, 2011, and was observed to have a maximum magnitude of Mw = 9.0 in Japan. This earthquake occurred along a very long interval of plate destruction running from the Ibaraki Prefecture offshore from the Iwate Prefecture off the coast, and involved a long-lasting ground motion. A list of waveforms observed during the Great East Japan Earthquake is shown in Figure 1. Conversely, the Hyogoken Nambu Earthquake that occurred on January 17, 1995 was an inland earthquake that occurred at the Rokko fault and the Nojima fault, and had a short duration. In this study, we use the seismic waves observed during the Great East Japan and the Hyogoken Nambu earthquake, and carry out cyclic torsional shear tests. From the result, we evaluate the influence which the difference of earthquake duration has on the liquefaction strength of the samples being tested. The waveforms from the Great East Japan Earthquake that were observed in the cities of Urayasu and Haramachi and those from the Hyogoken Nambu Earthquake that Kobe Meteorological Observatory and the Kobe East Bridge are shown in Figure 2. The Cyclic torsional shear test apparatus is shown in Figure 3.

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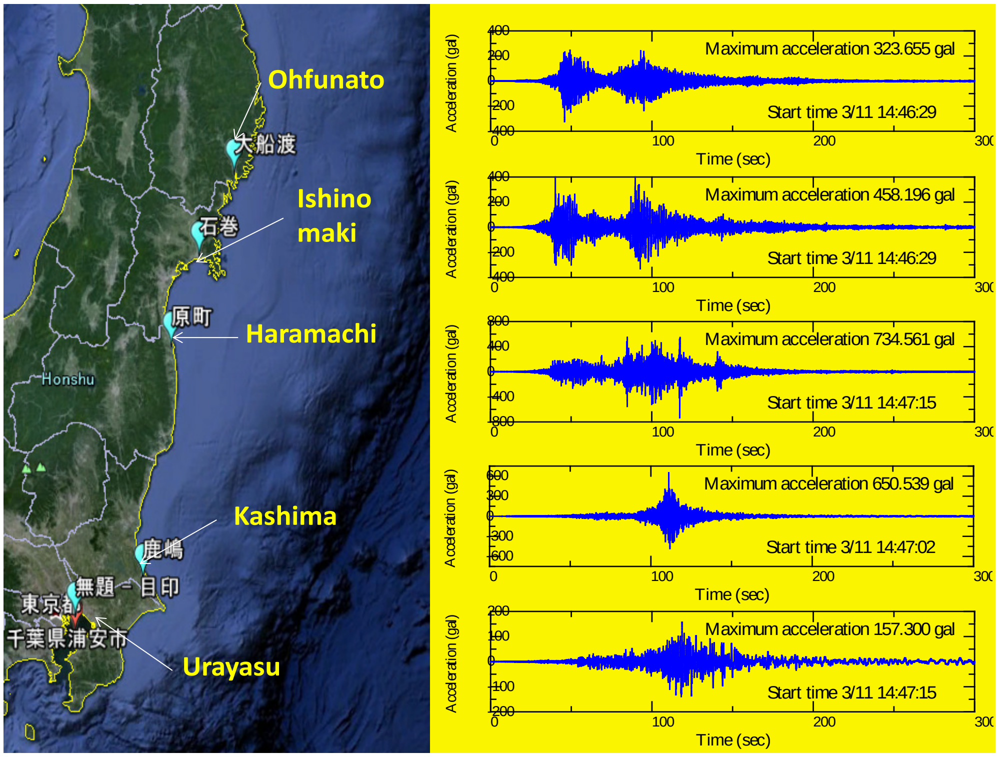

Figure 1: Wave forms observed during the Great East Japan Earthquake.

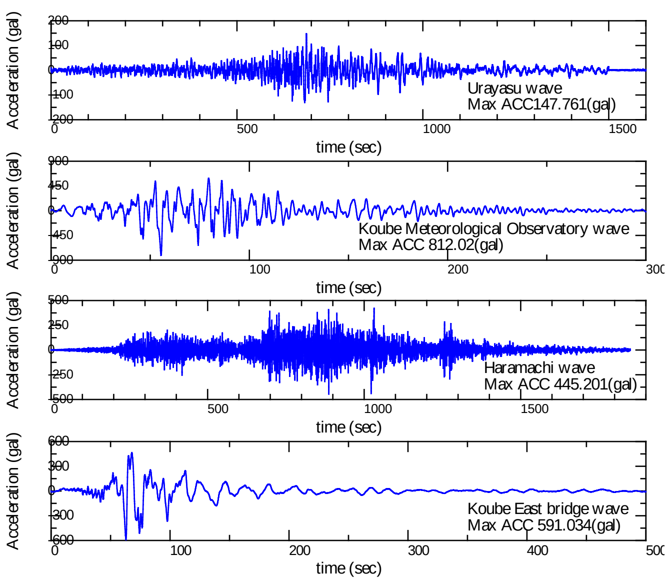

Figure 2: Wave forms used in the tests, as observed during Great East Japan Earthquake and the Hyogoken Nambu Earthquake

Figure 3: Cyclic torsional shear test apparatus.

A liquefaction test was already conducted (Ishikawa et al., 2014), using a sine wave and the Urayasu wave. The test sample consisted of Urayasu sand, which boiled during the Great East Japan Earthquake. The test result is shown in Figure 4; in this result, the liquefaction strength ratio of Urayasu sand treated with a sine wave was order 0.212~0.444, whereas when it is treated by the actual Urayasu wave, it was order 0.299~0.526. Then the liquefaction strength under Urayasu seismic wave was about 1.2 times compare with that under sine wave in the previous test.

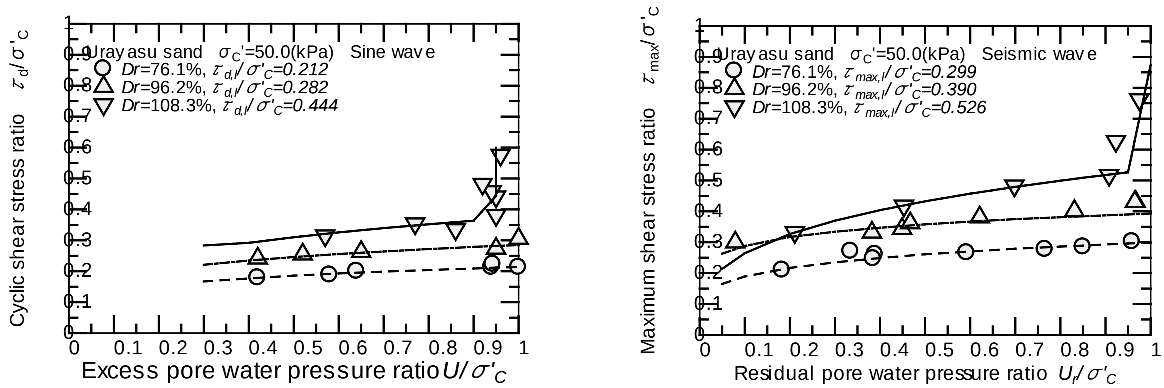

Figure 4: Liquefaction strength test using Urayasu sand with a sine wave and the actual Urayasu seismic wave (Ishikawa et al., 2014).

Test Procedure

Liquefaction strength was tested using a cyclic torsional shear test apparatus. The samples in this experiment comprised Toyoura sand, which was shaped into hollow cylindrical specimens. The outer diameter, inner diameter, and height of the specimens were 10 cm, 6cm, and 10 cm, respectively. The test specimens were made by air pluviation method. The density was set to a relative density of 50% and 70%. The specimens were then saturated and consolidated. The confining pressure was adjusted to 50 kPa.

Test Result

The liquefaction strength ratio was evaluated according to the method of Ishihara and Yasuda (1972). Figure 5 shows the result of the examination using the Kobe Meteorological Observatory wave. When the loading with seismic waves was completed, the excess pore water pressure ratio increased, and this excess pore water pressure ratio corresponded to the residual excess pore water pressure ratio Ur / σ'_c. Moreover, the maximum load amplitude that acted on this occasion corresponded to a maximum shear stress ratio τ_{max} / σ'_c. When the maximum shear stress ratio increased, the excess pore water pressure ratio also increased. Figure 6 is a conceptual diagram of the relationship between Ur / σ'_c and τ_{max} / σ'_c. From multiple examination results that relatively changed the stress level, we defined $Ur / \sigma'_c = 0.95$ as the liquefaction strength ratio, $\tau_{max,l,U} / \sigma'_c$.

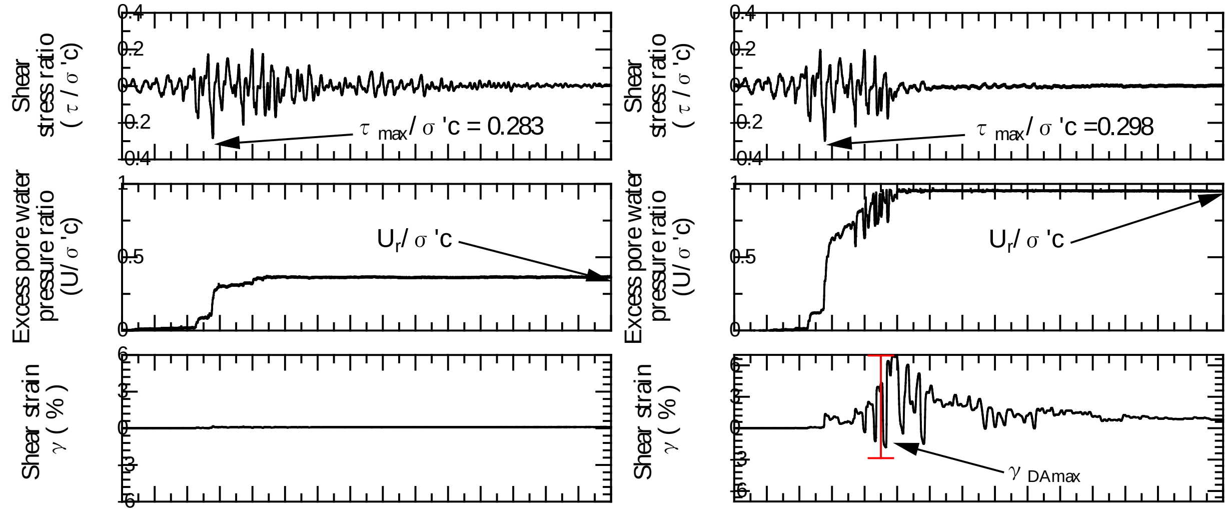

Figure 5: Test results using the Kobe Meteorological Observatory wave form.

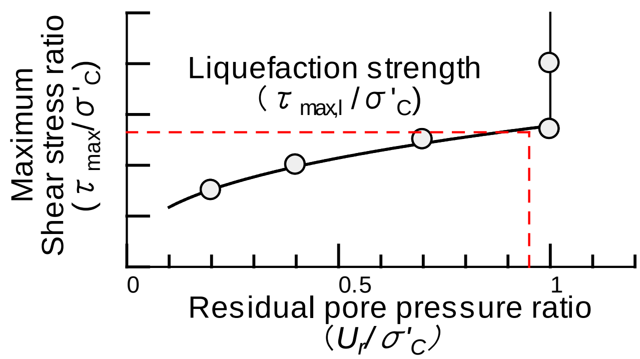

Figure 6: Definition of liquefaction strength.

The liquefaction strength curves that based on pore water pressure of each relative density by each waveform are shown in Figures 7 and 8. These figures show, as their test result, the tendency for excess pore water pressure to increase along with the value of a very small quantity of shear stress for each value of relative density. Moreover, the increase of liquefaction strength was confirmed to follow the increase of the relative density.

Table 1 shows the effective wave number of seismic waveforms that counted the wave number more than 80% to 50% of maximum acceleration. Among them wave number more than 60% is selected, as same as Yamazaki and Emoto (2012), and plotted with the liquefaction strength ratio in Figure 9 In this figure, a decrease of the liquefaction strength ratio has been confirmed with the increase of the effective wave number.

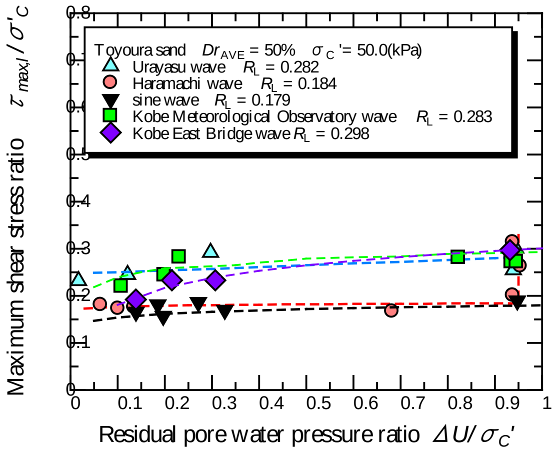

Fig. 7 Test result of seismic wave for Dr = 50%

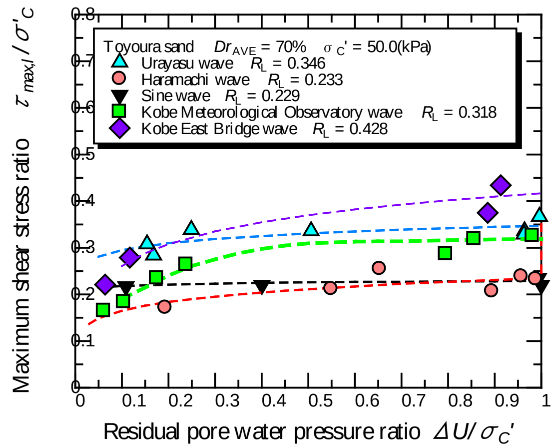

Fig. 8 Test result of seismic wave for Dr = 70%

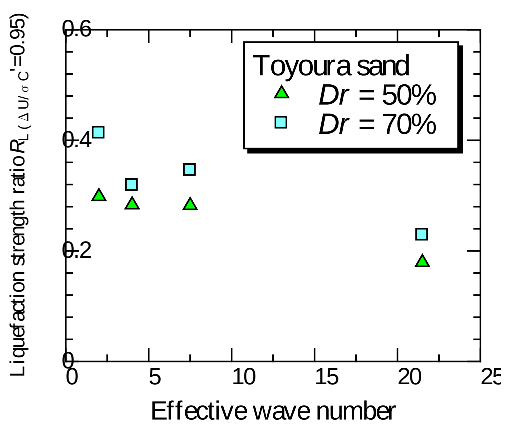

Figure 9: Relationship between effective wave number and liquefaction strength ratio.

Table 1. Effective wave number of each seismic wave form.

Valid wave criteria	80%	70%	60%	50%
Urayasu wave	2	2.5	7.5	14
Haramachi wave	4	7.5	21.5	43
Kobe Meteorological Observatory wave	0.5	1.5	4	5.5
Kobe East Bridge wave	1	1.5	2	2

Coefficient of the Irregularity of Seismic Wave Loading

The liquefaction strength ratio R as shown by the Japan Road Association (2012) was set by considering the irregularities of the seismic wave multiple liquefaction strength ratio, as seen in the general liquefaction test with a sine wave, and a correction factor due to the ground motion characteristics, C_W. According to the Japan Road Association, C_W under level 2 type 1 ground motion (plate boundary earthquake motion) is 1.0. In this case, we calculated each seismic wave of the C_W at test results that were observed during the Great East Japan earthquake and the Hyogoken Nambu earthquakes. The correction method for the liquefaction strength ratio under sine wave loads was proposed by Iwasaki and Tatsuoka (1978) as the following equation:

$$R = C_1 \times C_2 \times C_3 \times C_4 \times C_5 \times R_L \tag{1}$$

where C_1 is the weighting factor of the confining pressure ($C_1 = (1 + 2K_0)/3$), C_2 is the weighting factor of the irregular nature of earthquake motion, C_3 is the weighting factor of the disturbance from sampling to test, and C_4 is the weighting factor of the increase of value in the density from sampling to test. Evaluation of C_3 and C_4 is difficult to be considered as 1.0. C_5 is the weighting factor of the two-directional property of earthquake motion. R_L is the liquefaction strength ratio at the time of a double-amplitude shear strain occurring 7.5%, when sine wave loading is made to act 20 times. C_W is the product of the coefficients from C_1 to C_5. In this study, we pay attention to C_2 to grasp the effect of each ground motion. The coefficient of the irregularity of the seismic wave loading is the relation of the ratio of the liquefaction strength ratio to seismic wave loading ($\tau_{max,l} / \sigma'_c$) and liquefaction strength to sine wave loading, ($\tau_{d,l} / \sigma'_c$). This coefficient, C_2 is given by the following formula:

$$C_2 = (\tau_{max,l} / \sigma'_c) / (\tau_{d,l} / \sigma'_c) \tag{2}$$

The past test conducted by Ishihara and Yasuda (1972) used a vibration-type earthquake based on data taken from the Tokachi-oki earthquake of 1968. In that result, C_2 ranged from 1.43 to 1.82 (average 1.62).

Relationship between the Coefficient of the Irregularity of Seismic Wave Loading and the Relative Density

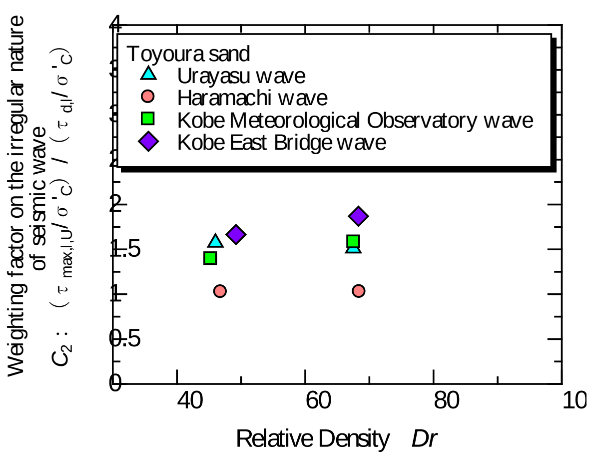

Figure 10: Relationship between relative density and C_2.

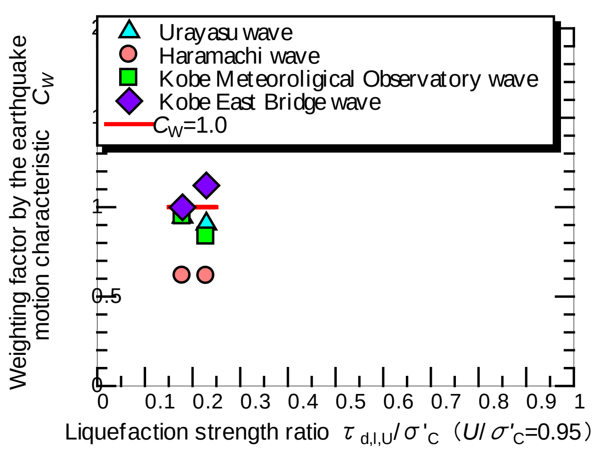

Figure 11: Relationship between the liquefaction strength ratio by sine wave and C_W.

The results and past studies (2014) concerning the relationship between C_2 for each seismic wave and the relative density are shown in Figure 10. Each seismic wave at C_2 differed in its waveform, but each wave at C_2 did not differ much by relative density. Because of this, the C_2 in specimens with a relative density of 70% or less were not affected by the waveform. This trend was the same as that shown in Yamazaki and Emoto (2012).

Correction Coefficient of Seismic Properties

Based on the results of this study and past studies, the relationship between C_W and the liquefaction strength ratio using a sine wave is shown in Figure 11. Comparing the waveforms observed during the Great East Japan and Hyogoken Nambu earthquakes, we found that C_W for the Great East Japan Earthquake was the smaller than C_W for the Hyogoken Nambu Earthquake.

Conclusions

This study reported on a cyclic shear test used to determine the liquefaction due to waveforms observed during the Great East Japan and Hyogoken Nambu earthquakes. The following conclusions were made:

1) The liquefaction strength ratio due to the Great East Japan Earthquake with a large effective wave number was smaller than that due to the Hyogoken Nambu Earthquake with a small effective wave number.
2) The relationship between the relative density and C_2 was not affected by the seismic waveform when the relative density was less than 70% or less.

Acknowledgment

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