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LIQUEFACTION CHARACTERISTICS OF CRUSHABLE VOLCANIC SOIL "SHIRASU"

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ABSTRACT

Previous liquefaction studies on volcanic soils generally concentrate on the fines contained within sandy volcanic soils; however, typical Shirasu volcanic soil has a high coefficient of uniformity and contains 20-30% gravel and non-plastic fines. A series of undrained cyclic shear tests was performed on dense samples of Shirasu to assess the influence of grain size distribution on the liquefaction susceptibility. The relative densities Dr of samples were 50% (loose) and 90% (dense). Testing was carried out on various combinations of the gravels, the sands and the fines. The tests were also carried out over a range of confining stresses. In the case of loose Shirasu, three different kinds of cyclic strength characteristics were defined in this study. First, for sandy Shirasu without gravel the cyclic strength increases with increasing confining pressure. Second, the cyclic shear strength of sandy soil with gravel is independent of initial confining pressure. Third, for gravely Shirasu the cyclic shear strength decreases significantly with increasing confining pressure. On the other hand, the results of dense Shirasu clearly demonstrated that the effect of initial confining pressure on cyclic shear strength for dense volcanic soil differs for different grain size distributions.

Keywords: Cyclic shear, Volcanic soil, Particle size distribution, Confining pressure.

INTRODUCTION

During the 1995 Great Hanshin earthquake, reclaimed land that had been filled with Masado soil suffered major liquefaction-related damage. Masado soil is a crushable residual granite soil. In addition to decomposed granites, Japan also has large areas covered by crushable volcanic ash sediments. These sediments are particularly widespread in southern Kyushu where they are known as Shirasu. Shirasu is an unusual soil, and problems can occur due to slope failure in heavy rain and seismic-induced liquefaction in alluvial and reclaimed land. During the 1968 Ebino earthquake, liquefaction was observed on plains and river terraces formed of Shirasu soil, and subsidence of bridge piers was reported. During the 1997 Kagoshima ken Hokuseibu earthquake, structural damage related to liquefaction was observed in areas of coastal land reclamation. Shirasu is commonly pumped from inland locations as a slurry to form a loose saturated fill. Widespread liquefaction-related damage during the 1964 Niigata earthquake led to a large research effort concentrating on the liquefaction properties of silica sands in harbors and estuaries. Liquefaction studies have also been carried out on Shirasu since the Ebino earthquake, but little attention has been paid in these studies to the unique characteristics of volcanic soils.

Failure of volcanic soils during earthquakes is common in Japan (Ishihara and Harada, 1996; Miura and Yagi, 1995). Liquefaction of volcanic soils was observed during the 2003 Tokachioki earthquake

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in Hokkaido, Japan. Failures are also known to have occurred in Shirasu, which is commonly found in large areas of Southern Kyushu (Yamanouchi, 1968). Shirasu is also commonly used as a fill (Umehara et al, 1975). Both of the above mentioned soils are crushable; it is therefore important to extend the scope of liquefaction research to study the characteristics of crushable soils.

The authors have previously conducted monotonic and cyclic triaxial tests on three types of crushable soil: carbonate sand, Masado and Shirasu (Hyodo et al, 1998). The test results were been compared with those for a less crushable standard silica sand, Toyoura sand. The effect of both confining pressure and relative density on the shearing properties of these soils was considered.

Previous liquefaction studies on volcanic soils generally concentrate on the fines contained within sandy volcanic soils, however, typical Shirasu volcanic soil has a high coefficient of uniformity and contains 20-30% gravel and non-plastic fines. A series of undrained cyclic shear tests was performed on loose samples of Shirasu to assess the influence of grain size distribution on the susceptibility of the soil to liquefaction. The relative densities of samples were 50% (loose) and 90% (dense). Tests were carried out on various combinations of gravel (>2.00 mm), sand and fines (<0.075 mm) over a range of confining stresses.

MATERIALS AND EXPERIMENTAL METHODS

Materials

The material tested in this study was Shirasu sampled directly from the indurated deposit at Aira-gun, Hayatocho, Kagoshima prefecture, Japan. The original grain size distribution of this material is shown in Figure 1. The original Shirasu contained approximately 15% gravel. The fines content (<0.075 mm) was approximately 20% but was non-plastic, containing the same materials as the parent material (Okabayashi et al., 1994; Hyodo et al., 1980). The density of soil particle ρ_s is 2.409 Mg/m^3. The density of soil particles of individual pumice grains within Shirasu is very low due to the occurrence of intraparticle occluded voids.

In this study we investigated the cyclic shear characteristics of seven types of graded Shirasu material. The physical properties of each material are listed in Table 1. The maximum and minimum dry densities of the soils were measured via the Japanese standard method. The dry densities of Shirasu were determined with the gravel and fines fractions included in the sample. In this method, Shirasu was placed in a cylindrical mould (V=1000 cm^3) 100 mm in diameter and 12.7 mm deep. The minimum dry density was determined by pouring the soil through a paper cone with a 30 degree angle and 40 mm diameter outlet. The base of the cone was kept close to the soil surface at all times to ensure the sand was evenly distributed across the surface. For determining the maximum dry density, a 20 mm extension piece was added to the mould and the soil was placed in ten 10 mm layers. The mould was tapped with a wooden mallet at a frequency of 5 Hz and amplitude of 50 mm for 20 s for each layer. The extension piece was then removed and the soil was leveled using a straight edge. The maximum and minimum dry densities for each Shirasu were greater than that for typical sand; this was particularly so for the minimum dry density. The particle size distribution curves are shown in Figure 1.

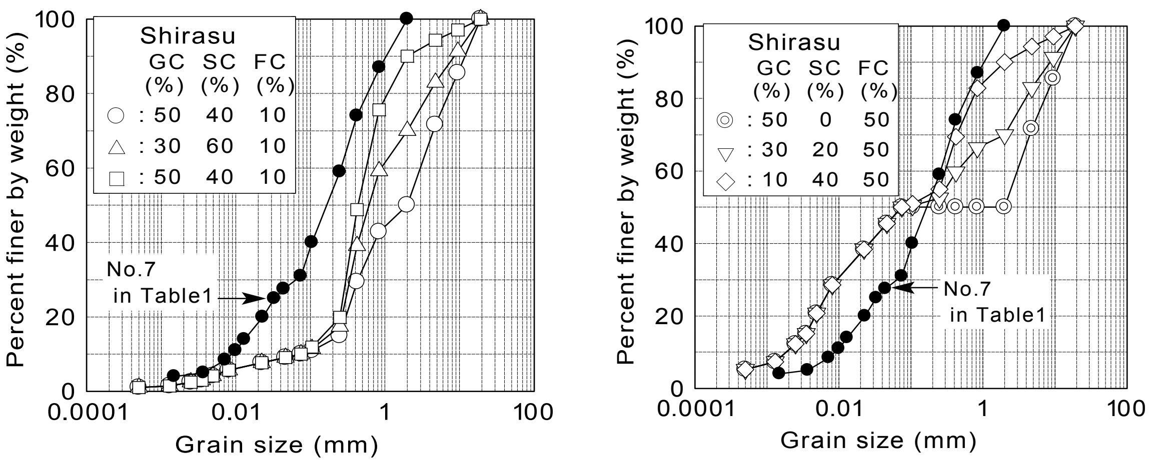
Experimental methods

The dimensions of the cyclic triaxial specimens were 75 mm in diameter and 150 mm in height. As Shirasu has a high fines content and varying specific gravity of individual grains, neither air nor water pluviation was used. Instead, the required mass of material was weighed out and a loose sample was prepared by gently rodding the material into the mould. The required relative density was then achieved by tapping the mould until the volume had reduced to the required value under dry conditions. The formed sample of Shirasu was then put under de-aired water for 10 minutes. After each specimen was drained, the unsaturated specimens were frozen for more than 2 hours. The sides of the frozen specimens were then covered in sand owing to a reduction in membrane penetration. Relative densities of 50% (loose) and 90% (dense) were tested for this material, respectively.

After each specimen was set up in the cell, the frozen specimen was allowed to melt under an effective confining stress of 19.6 kPa for 2 hours. To achieve full saturation, all specimens were saturated using the methods proposed by Rad and Clough (1984) and JGS (2000). De-aired water was subsequently permeated into the voids at small different head (4.9 kPa). A back pressure of 100kPa was applied to produce a B value greater than 0.96. Cyclic undrained triaxial tests were performed following the application of the required cell pressure. Specimens were isotropically consolidated to 50, 100, 300, 500 kPa and then subjected to cyclic load tests. Cyclic tests were performed under stress controlled conditions with a sinusoidal load applied by a pneumatic actuator at a frequency of 0.1 Hz.

Table 1 Physical properties of the seven materials tested in this study.

No.	Grain Content			ρ_{dmax}	ρ_{dmin}	D_{50}	σ_c'
	Gravel (G.C.) (%)	Sand (S.C.) (%)	Fine (F.C.) (%)	(Mg/m^3)	(Mg/m^3)	(mm)	(kPa)
1	50	40	10	1.319	1.050	2	50 100 300 500
2	50	0	50	1.257	1.044	0.073	
3	30	60	10	1.314	1.039	0.68	
4	30	20	50	1.502	1.157	0.073	
5	10	80	10	1.471	1.125	0.38	
6	10	40	50	1.418	1.066	0.073	
7	0	70	30	1.402	0.998	0.165	



(a) **(b)**

Figure 1. Particle size distribution of the Shirasu sample for (a) FC=10% and (b) FC=50%

UNDRAINED CYCLIC SHEAR CHARACTERISTICS

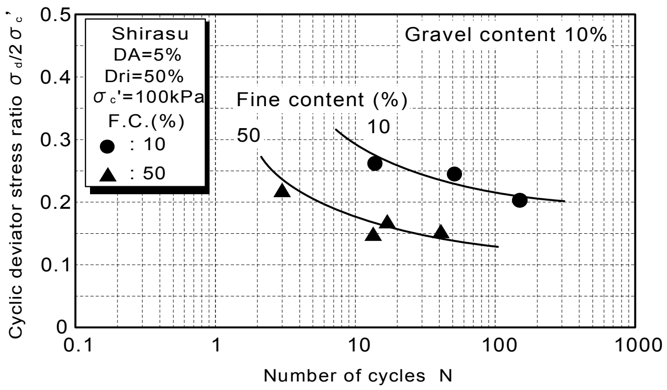
Effect of particle size distribution on cyclic shear strength curve

Researchers have traditionally defined liquefaction failure as a double amplitude strain: DA = 5% (Ishihara, 1994). This definition allows for the inclusion of both cyclic mobility and classical liquefaction failures. Cyclic strength is defined as the normalized cyclic deviator stress $\sigma_d/2\sigma_c'$ required to cause failure after a given number of cycles.

Loose Shirasu

The effect of fines content on the cyclic strength of loose Shirasu is shown in Figures 2a-b.The cyclic strength of Shirasu with 10% gravel content decreased with increasing fines content for all values of confining stress (Figure 2). In Figure 2b, however, the cyclic strength curves for samples with 10%

and 50% fines content plot in a similar position even after 100 cycles; there appears to be a dependence on the magnitude of the confining pressure. The cyclic strength curve at 50% fines content becomes flatter and resembles the curve for very loose sand. The Shirasu that contains fines has a weak structure that consists of fine particles in the voids between larger grains. At low confining pressure, the fine particle structures collapsed under cyclic loading, resulting in liquefaction. As the initial confining stress was increased, the fine granite structure became compressed and thus the soil matrix became stiffer under cyclic loading.



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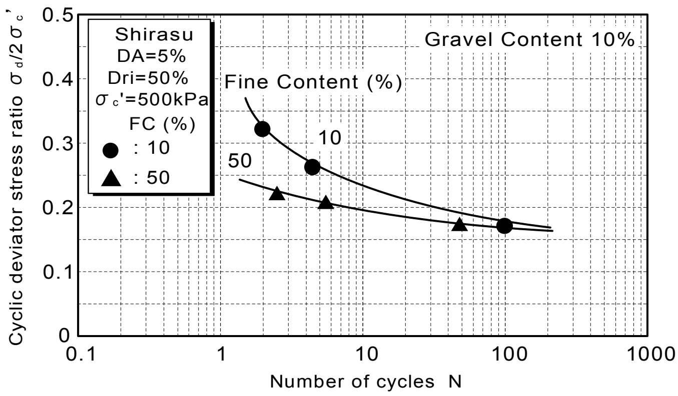


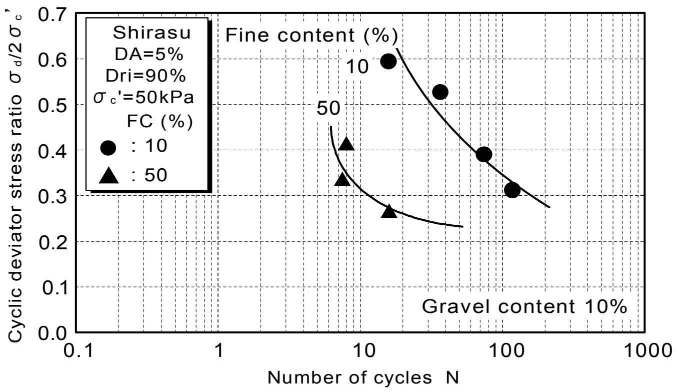
(b)

Figure 2. Effect of fines content on cyclic strength curves for loose Shirasu;(a) σ_c' = 100 kPa and (b) σ_c' = 500 kPa

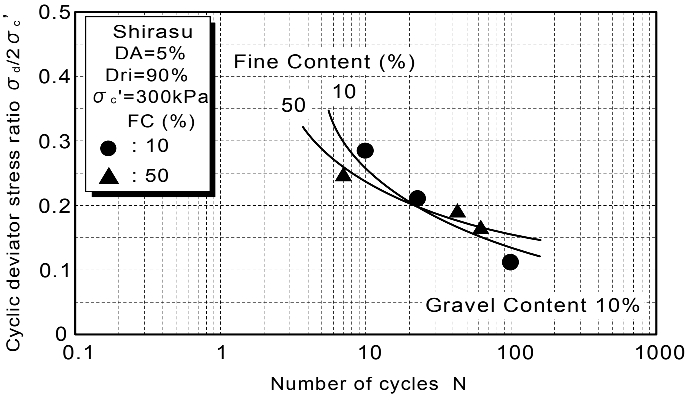
Dense Shirasu

The effect of fines content on the cyclic strength of dense Shirasu is shown in Figure 3a-b. In Figure 3a as is frequently seen with dense sand there is a steep rise in both of cyclic strength curves for less than 10 cycles. For an initial confining pressure σ_c'=50kPa, the cyclic shear strength of Shirasu with 10% gravel content is greater than that with 50% fines content. In this case there appears to be a fine content dependence. In Figure 3b, however, the cyclic strength curves for samples with 10% and 50% fines content are plotted in a similar position. There appears to be a dependence on the magnitude of the confining pressure, but neither of these was affected by fine content. In addition, the cyclic strength curve at both fines contents becomes flatter and resembles the curve for loose sand.

The Shirasu that contains fines has a weak structure that consists of fine particles in the voids between larger grains. For Shirasu with 50% fine content, the fine particle structures collapsed under cyclic loading at each confining pressure. On the other hand, for dense Shirasu with 10% fine content, it is considered that the void between the larger grains did not any content smaller grains. As the initial confining stress was increased, this led to a high level of crushing and collapse of the larger grain structure under cyclic loading resulting in the cyclic strength that was similar to that for dense Shirasu with 50% fine content.



(a)



(b)

Figure 3. Effect of fines content on cyclic strength curves for dense Shirasu;(a) σ_c' = 50 kPa and (b) σ_c' = 300 kPa

Effect of initial confining pressure on cyclic shear strength

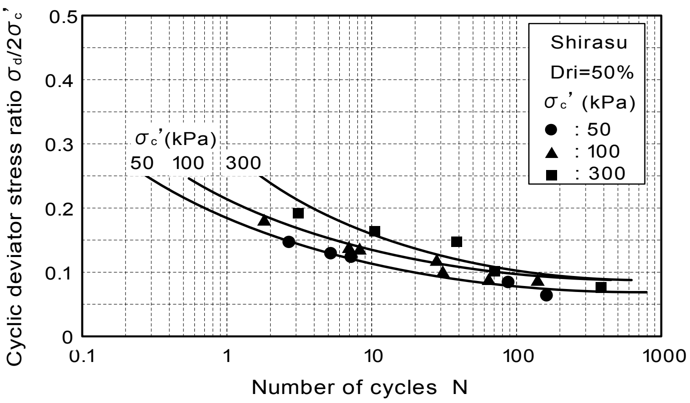
Loose Shirasu

Figures 4a-c show plots of stress ratio $\sigma_d/2\sigma_c'$ against number of cycles N required to generate liquefaction failure.

The data for sandy Shirasu without gravel is shown in Figure 4a. In this case there appears to be a dependence on confining pressure. The cyclic strength of the sample increased with increasing confining pressure.

The cyclic shear strength for sandy Shirasu with gravel is shown in Figure 4b. The magnitude of the initial confining pressure does not appear to influence cyclic shear strength. A similar trend has been observed for loose silica sand (Ishihara et. al., 1983).

In contrast to the sandy Shirasu without gravel, the cyclic shear strength of gravely Shirasu decreases markedly with increasing confining pressure as shown Figure 4c. Although deposits of gravely Shirasu are loose, this result is similar to the cyclic shear strength characteristics of dense crushable soils such as volcanic soil, decomposed granite soil, and carbonate sand (Hyodo et al,1998).



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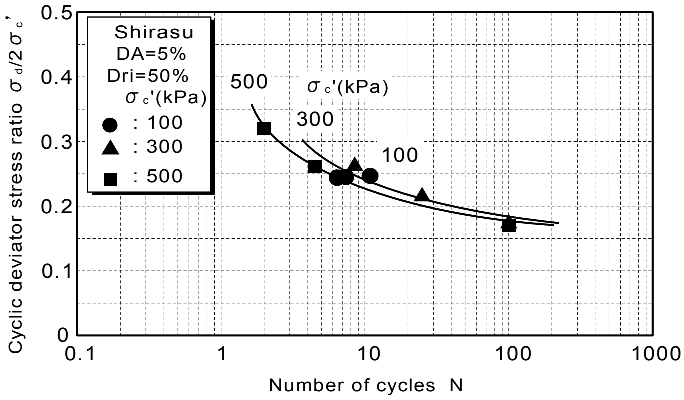

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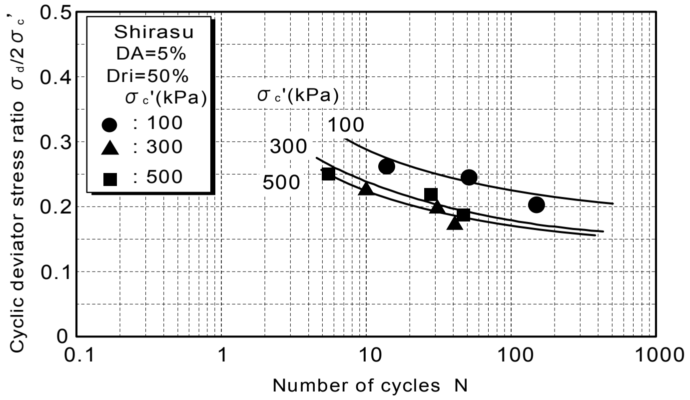


(c)

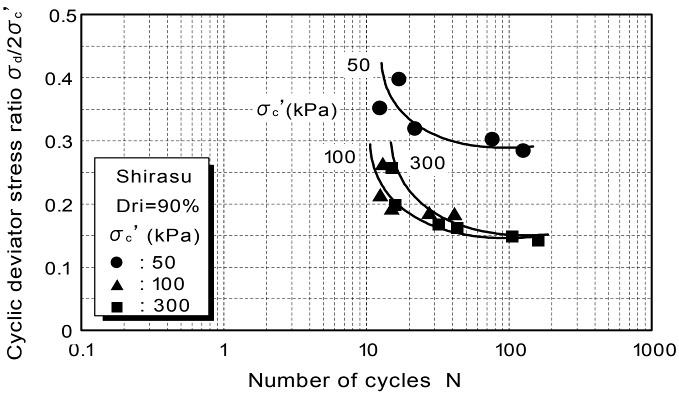
Figure 4. Effect of confining pressure on cyclic strength curves for loose samples; (a) sandy Shirasu without gravel (No.7 in Table 1), (b) sandy Shirasu with gravel (No.5 in Table 1) and (c) gravely Shirasu (No.1 in Table 1).

Dense Shirasu

The data for sandy Shirasu without gravel is shown in Figure 5a. In this case there appears to be a dependence on confining pressure. The cyclic strength of the sample decreases with increasing confining pressure. It can be seen that the cyclic strength decreases as the confining pressure is increased from 50kPa to 100kPa. However, the cyclic strength curves for samples with initial confining pressure 100 and 300kPa plot in a similar position.

For sandy Shirasu with gravel as shown in Figure 5b, the cyclic strength curves for 50kPa and 100kPa are very close to each other. The nature of the confining pressure dependence is unclear; however, it can be seen that the cyclic strength decreases as the confining pressure is increased from 100 to 300kPa.

In Figure 5c, there appears to be a confining pressure dependence for gravely Shirasu, with the cyclic strength decreasing as the confining pressure increases. At 300kPa the cyclic strength curve becomes flatter such as loose sand and clay (Hyodo et al, 1994).



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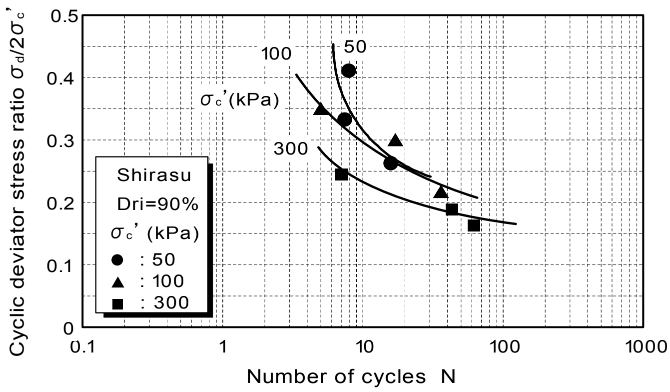

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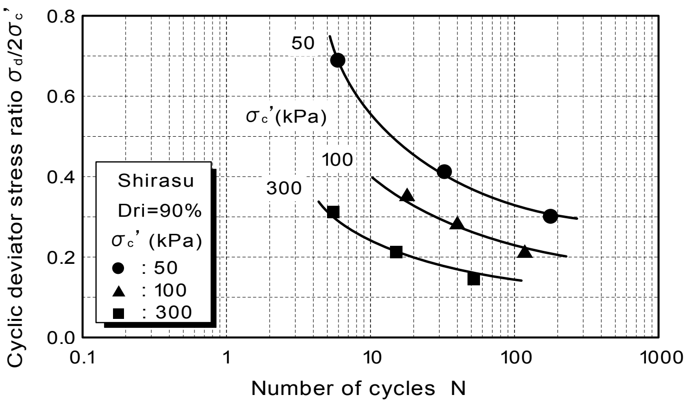


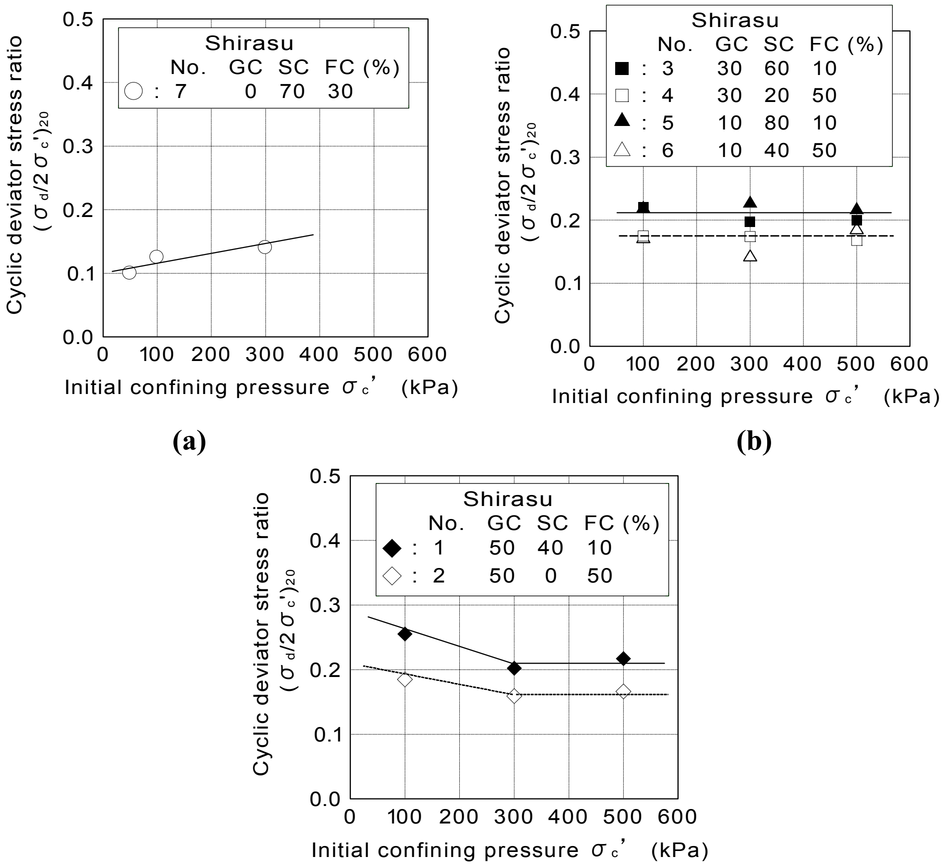
(c)

Figure 5. Effect of confining pressure on cyclic strength curves for dense samples; (a) sandy Shirasu without gravel (No.7 in Table 1), (b) sandy Shirasu with gravel (No.6 in Table 1) and (c) gravely Shirasu (No.1 in Table 1).

Relationship between the cyclic stress ratio required to cause failure after 20 cycles and initial confining pressure

During earthquakes, liquefaction occurs after only a few cycles of loading. A useful way of defining the susceptibility of a soil to liquefaction failure, therefore, is to define a single point strength as the cyclic deviator stress ratio required to cause failure after 20 cycles. In Figure 6 a to c, the normalized deviator stress required to cause liquefaction failure after 20 cycles $(\sigma_d/2\sigma_c')_{20}$ is plotted against the initial confining pressure σ_c' for loose Shirasu.

The normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ for sandy Shirasu without gravel increased with increasing confining pressure (Figure 6a). For the same fines content, the normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ for sandy Shirasu with gravel (Test No.3 to 6 in Table 1) is independent of confining pressure (Figure 6b). For gravely Shirasu the normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ decreased with increasing confining pressure (Figure6c).



(c)

Figure 6. Relationship between the cyclic stress ratio required to cause failure after 20 cycles and initial confining pressure for loose samples ; (a) sandy Shirasu without gravel, (b) sandy Shirasu with gravel and (c) gravely Shirasu

In Figure 7 a to c, the normalized deviator stress required to cause liquefaction failure after 20 cycles $(\sigma_d/2\sigma_c')_{20}$ is plotted against the initial confining pressure σ_c' for dense Shirasu. The normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ for sandy Shirasu without gravel decreased with increasing confining pressure(Fig. 7a). In the case of sandy Shirasu with gravel (Test No.3 and 5 in Table 1), the normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ for 10% fines content decreases markedly with increasing confining pressure(Fig. 7b). On the other hand, for each 50% fines content (Test No.4 and 6 in Table 1), the normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ for σ_c' is equal to 50kPa and 100kPa are similar, and the corresponding strength for σ_c'=300kPa is different. The cyclic strengths for sandy Shirasu with 30%

gravel content are greater than those for sandy Shirasu with 10% gravel content at σ_c' =50kPa. Fig. 7b also shows the normalized deviator stresses for σ_c' =300kPa are very close to each other.

For gravely Shirasu(Test No.1 and 2 in Table 1) the normalized deviator stress $(\sigma_d/2\sigma_c')_{20}$ decreased markedly with increasing confining pressure (Figure 7c). It can be seen that the normalized deviator stresses for 10% and 50% fine content are very similar at σ_c' =100kPa. Fig. 7c also shows the same tendency for the normalized deviator stress at σ_c' = 300kPa. It is recognized that there is no fine content effect on gravely Shirasu over this range of confining pressures.

The results of these experiments clearly demonstrate that the effect of initial confining pressure on cyclic shear strength for dense volcanic soil differs for different grain size distributions.

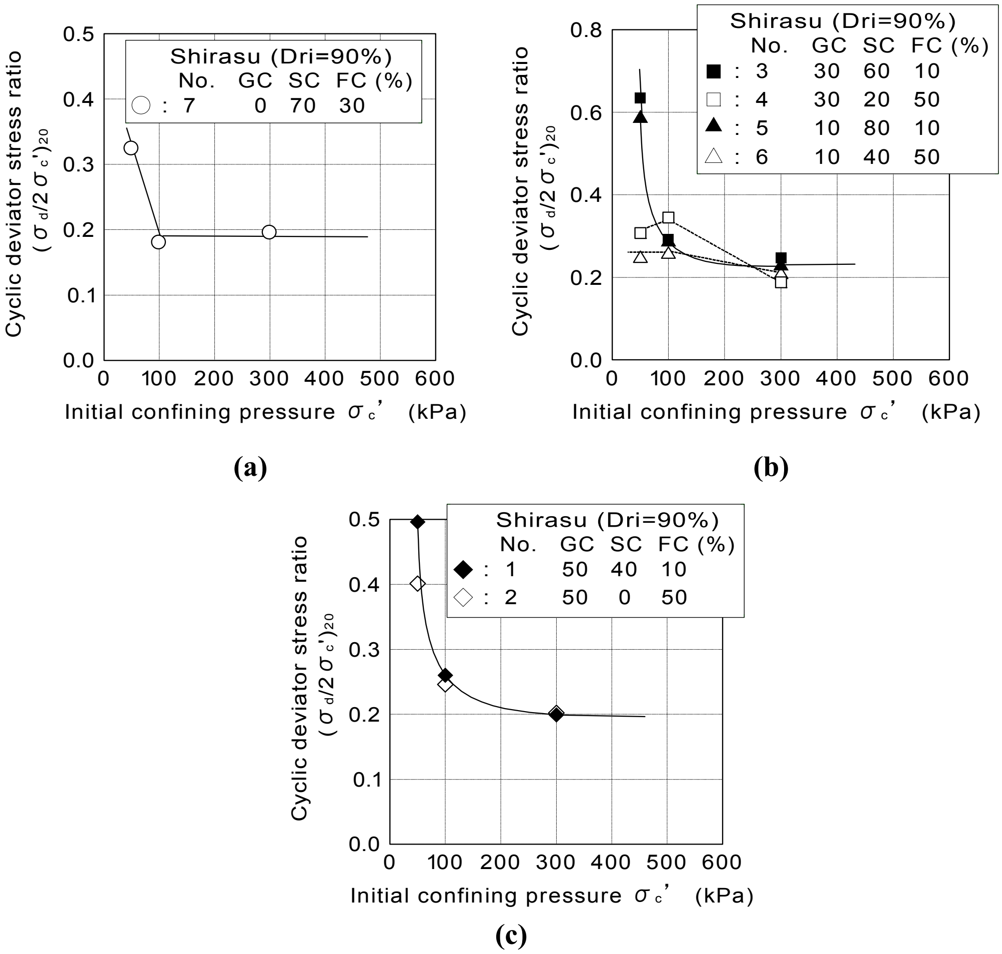


Figure 7. Relationship between the cyclic stress ratio required to cause failure after 20 cycles and initial confining pressure for dense samples ; (a) sandy Shirasu without gravel, (b) sandy Shirasu with gravel and (c) gravely Shirasu

CONCLUSIONS

We performed a series of undrained cyclic shear tests on dense samples of Shirasu to assess the influence of grain size distribution on the susceptibility of the soil to liquefaction. The following are the main conclusions derived from the tests. (1)In the case of loose Shirasu, three different kinds of cyclic strength characteristics were defined in this study. First, for sandy Shirasu without gravel the cyclic strength increases with increasing confining pressure. Second, the cyclic shear strength of sandy soil with gravel is independent of initial confining pressure. Third, for gravely Shirasu the cyclic shear strength decreases significantly with increasing confining pressure. (2)The results of dense Shirasu clearly demonstrated that the effect of initial confining pressure on cyclic shear strength for dense volcanic soil differs for different grain size distributions.

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