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ТЕХНИЧЕСКИЕ НАУКИ И ТЕХНОЛОГИИ

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Influence of compaction conditions on the liquefaction characteristics of pumice sand with non-plastic fines

Abstract. *In this study, the liquefaction characteristics of pumice sand were investigated focusing on the relationship with compaction conditions. The new findings obtained in this study are summarized as follows. In the pumice sand with a large amount of non-plastic fines, liquefaction resistance R_{L20} can be expected to be only about 0.2 at a degree of compaction of 90%, however, it can be increased to be 0.3 or more if the soil is densified by compaction up to degree of compaction of 95% or more. In addition, the skeletal structure is also important even at the same dry density, and a higher liquefaction resistance can be expected under the compaction conditions on a dryer condition in water content at compaction. On the other hand, the tenacity for deformation in liquefaction under cyclic loading may be lost in the compaction conditions on the dryer condition, so the tenacity for liquefaction should also be noted.*
Keywords: *pumice sand, volcanic sand, non-plastic fines, liquefaction, compaction condition, cyclic loading triaxial test.*

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1. Introduction

Satozuka District of Kiyota Ward in the southern part of the City of Sapporo is located almost at the end of a plateau consisting of pyroclastic flow deposits (Spfl) ejected by eruption of Shikotsu Volcano about 40 000 years ago. The Shikotsu Volcano is a large caldera lake today due to the eruption. In the 2018 Hokkaido Eastern Iburi Earthquake that occurred on September 6, 2018, an earth-fill constructed in a valley at the end of the plateau liquefied over a wide area, causing enormous damage [1]. The pumice sand in this region is characterized as a large content of non-plastic fines if it is compared to that found in previous studies [2][3]. In this study, we investigated the liquefaction characteristics of pumice sand with non-plastic fines, which is the earth-fill material in the Satozuka district, focusing on the compaction conditions.

2. Soil sample

The pumice sand examined in this study was a soil sample excavated and collected at Satozuka Chuo Popura Park where is one of the damage areas liquefied due to the 2018 Hokkaido Eastern Iburi Earthquake. The grain size distribution curve of the pumice sand is shown in Figure 1. It is characterized by a wide range in grain-size distribution, a high non-plastic fine particles (less than 0.075 mm) content of about 45%.

In the following, the sample name is referred to as F45 reflecting the value of fine content. Since the grain size distribution of the sample collected immediately after the earthquake was slightly different from that of the sample collected one year after the earthquake, the sample name was distinguished as FB45. In addition, pumice sand artificially prepared by reducing fine particle content from 45% to 40% and 20%, and call them F40 and F20, respectively. The physical properties of the sample are tabulated in Table 1. The maximum dry density ρ_{dmax} and the optimum water content w_{opt} are the values read from the compaction curve shown in Figure 2 obtained by the compaction test in non-repetitive method according to the A-c method of JIS A 1210. The minimum void ratio and the maximum void ratio are the values obtained by applying JIS A 1224 mutatis mutandis.

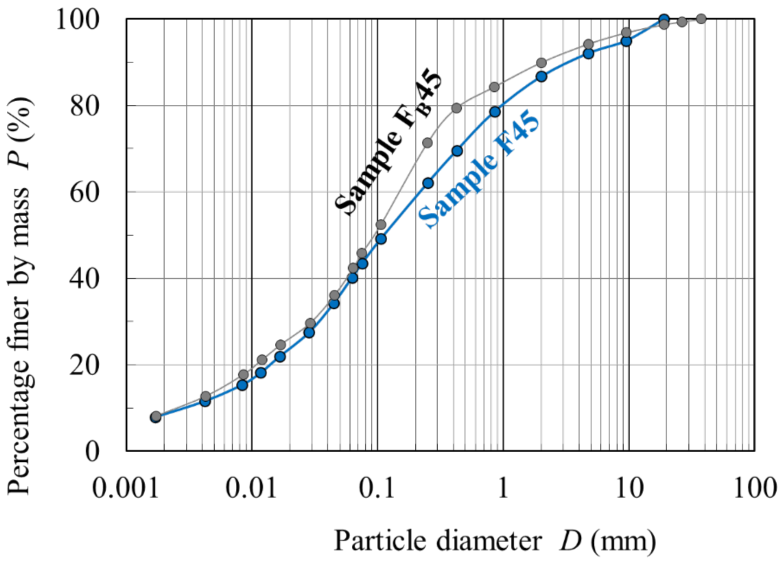

Figure 1. Grain-size distribution curve.

Table 1. Physical properties of the pumice sand

	F45	F_B45	F40	F20
Soil particle density ρ_s (Mg/m^3)	2.376	2.392	2.376	2.376
Maximum dry density ρ_{dmax} (Mg/m^3)	1.068	1.094	-	-
Optimum water content w_{opt} (%)	42.7	42.7	-	-
Minimum void ratio e_{min}	1.405	1.276	1.269	1.594
Maximum void ratio e_{max}	2.494	2.194	2.172	2.557

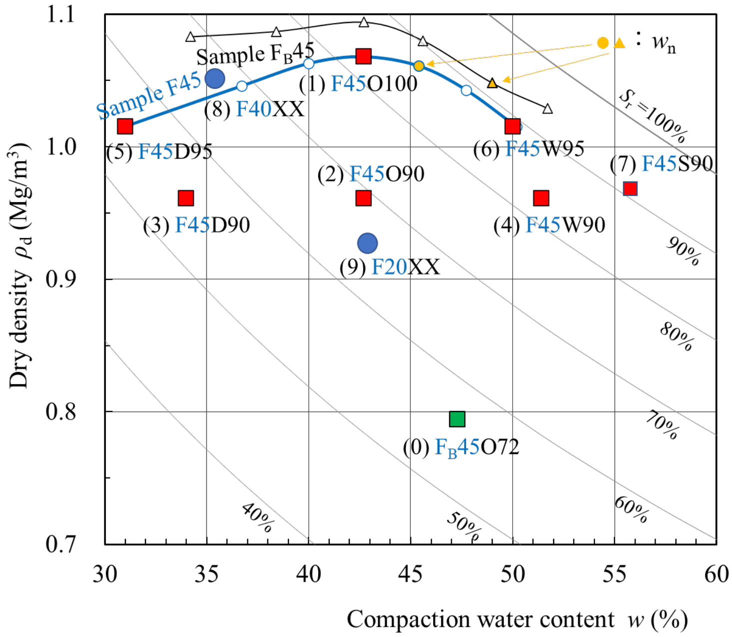

Figure 2. Compaction conditions

3. Test conditions and test procedure

Specimens for triaxial test were prepared by statical compression in the mold to be densified to the target dry density. The compaction conditions of the specimen are plotted in Figure 2, and the loading conditions of the cyclic loading undrained triaxial test are tabulate in Table 2.

The numbers in brackets in the test case name indicate the order in which the tests were conducted, followed by sample name consisting of alphabet and number indicating the fine particle content, and the next alphabet indicates the vicinity of the optimum water content (O), and dryer side (D) or wetter side (W) than that, and the number following it is the value of the compaction degree D_c. In addition, in consideration of that the skeletal structure of the compacted soil is generally governed by degree of saturation at compaction even if the soil is non-plastic [4], the compaction conditions with different degree of compaction were set at the same degree of saturation in some cases.

Table 2. List of test cases

Test ID	At compaction				After consolidation		Consol. Press.	Cyclic loading stress ratio
	w_0 (%)	ρ_d (Mg/m^3)	D_c (%)	D_r (%)	D_c (%)	D_r (%)	σ'_0 (kPa)	$R = \tau/2\sigma'_0$
(0) F_B45O72	47.3	0.794	72.6	19.6	77.1	39.3	30	0.065, 0.080, 0.109
(1) F45O100	42.3	1.069	100.1	116.7	101.4	119.4	50	0.500, 0.652, 0.805, 0.902
(2) F45O90	42.7	0.963	90.1	94.2	91.3	97.0	50	0.150, 0.200, 0.300, 0.400
(3) F45D90	34.1	0.959	89.8	93.3	91.1	96.6	50	0.140, 0.199, 0.301, 0.450
(4) F45W90	51.2	0.964	90.2	94.4	98.3	99.0	50	0.141, 0.204, 0.300, 0.401
(5) F45D95	31.1	1.011	94.7	105.0	95.6	107.0	50	0.381, 0.500, 0.598, 0.803
(6) F45W95	46.9	1.017	95.2	106.3	96.5	109.2	50	0.251, 0.352, 0.500, 0.704
(7) F45S90	55.3	0.957	89.6	92.8	95.8	107.6	50	0.110, 0.139, 0.200, 0.299
(8) F40XX	35.6	1.051	-	99.9	-	102.1	50	0.501, 0.999, 1.507, 1.995
(9) F20XX	42.8	0.919	-	100.8	-	103.3	50	0.500, 0.802, 1.501, 2.007

Test case (0) FB45O72 is a specimen that reproduces the density of the embankment in the Satozuka area [1], which was damaged by the 2018 Hokkaido Eastern Iburi Earthquake. Test case (7) F45S90 is a specimen made by pouring a liquified sample with a target water content into a mold, i.e., without compaction. Its initial dry density was equivalent to a compaction degree of 90%, however, the dry density during the process of cyclic loading was equivalent to a compaction degree of 95% because it became dense during the saturation and consolidation process. Although F20 and F40 with reduced fine particle content are in a densely packed state, the part of test case name corresponding to the degree of compaction is indicated as XX because the volume of the soil sample was not enough for the compaction test.

Table 2 also summarizes the degree of compaction D_c and relative density D_r of the prepared specimens just after soil compaction (i.e., in the initial state) and after consolidation (i.e., during the cyclic loading). The specimen was saturated by carbon dioxide substitution method and applying back pressure of 100 kPa (200 kPa for FC20XX and FC40XX) with upward water infiltration to confirm that the Skempton's pore water pressure coefficient B value became 0.95 or higher. The effective consolidation pressure σ'_0 was set to 50 kPa (FB45O72 was 30 kPa). The cyclic stress ratio was set as appropriate values corresponding to two points each smaller and larger than 20 times of cyclic loading to reach liquefied state. Here, relationship between the cyclic stress ratio $R = \tau/2\sigma'_0$ and the number of loading cycles N_c will be described later in the section of test results.

4. Test results and discussion

From the test results obtained in the series of cyclic loading undrained triaxial tests, the number of loading cycles N_c when double amplitude strain DA reached 5% is read, and the relationship between the cyclic stress ratio $\tau/2\sigma'_0$ and the number of loading cycles N_c is plotted in Figure 3.

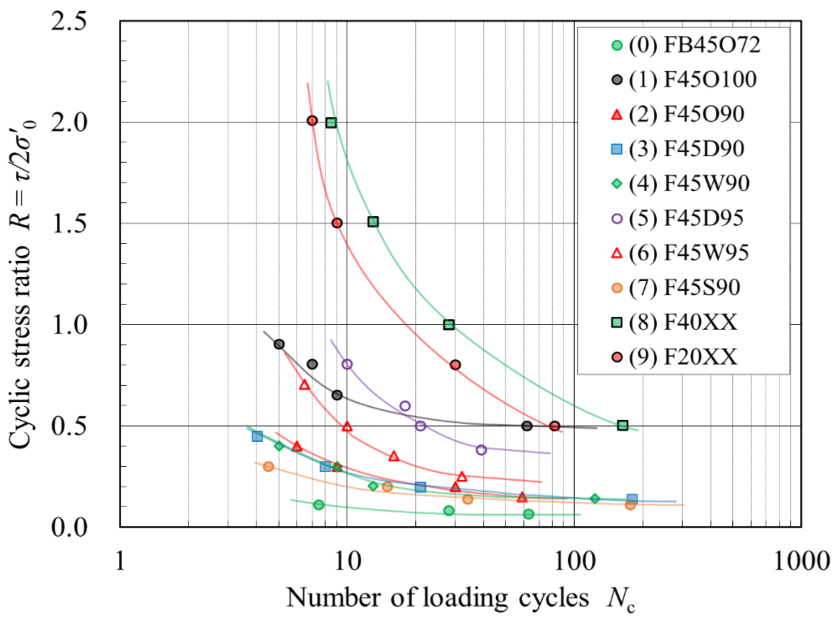

Figure 3. Relationship between cyclic stress ratio and number of loading cycles

The liquefaction resistance R_{L20} defined as the cyclic stress ratio $\tau/2\sigma'_0$ when the number of loading cycles N_c is 20 times and the double amplitude strain DA reaches 5% is about 0.5 for the (1) F45O100, which was densely compacted. Higher values of R_{L20} of around 1.0 were obtained for (8) F40XX and (9) F20XX. It is suggested that the liquefaction resistance R_{L20} increases by densification, while the liquefaction resistance R_{L20} tends to be smaller in the cases of sample F45 with a high fine particle content of 45%.

The liquefaction resistance R_{L20} of both (1) F45O100 and (5) F45D95 is almost the same as 0.5; however, when the cyclic stress ratio R is higher, (5) F45D95 with lower degree of compaction on dryer side has a higher liquefaction resistance. It can be said that the specimen compacted on dryer side shows a higher liquefaction resistance is consistent with (8) F40XX (with only 5% or less fine particles), which showed extremely high liquefaction resistance.

However, the liquefaction resistance R_{L20} of (6) F45W95 compacted on a wetter side is as low as about 0.3, indicating that even with the same degree of compaction as the above two cases, there is a nearly double difference in liquefaction resistance depending on the compaction conditions.

The density of F45S90 after pouring the liquified sample is essentially equivalent to degree of compaction of 95%, but the liquefaction resistance is lower than that of the test cases with degree of compaction of 90% described below. These differences in liquefaction resistance for the cases with the same degree of compaction (i.e., dry density) indicate that the liquefaction resistance strongly influenced by the skeletal structure. However, the liquefaction resistance R_{L20} was about 0.2 in all the cases of (2) F45O90, (3) F45D90, and (4) F45W90 with a degree of compaction of 90%, indicating that there was almost no difference in the liquefaction resistance among them. In the loosely packed (0) FB45O72, which corresponds to the in-situ state at damaged earth fill in Satozuka District in the City of Sapporo, the liquefaction resistance of R_{L20} is less than 0.1, indicating that it is significantly liquefaction prone.

As some typical test results in which it required about 25 times of cyclic loading to reach double amplitude strain DA of 5%, observed data for (1) F45O100, (5) F45D95, (6) F45W95 and (3) F45D90 are shown in Figures 4, 5, 6 and 7, respectively.

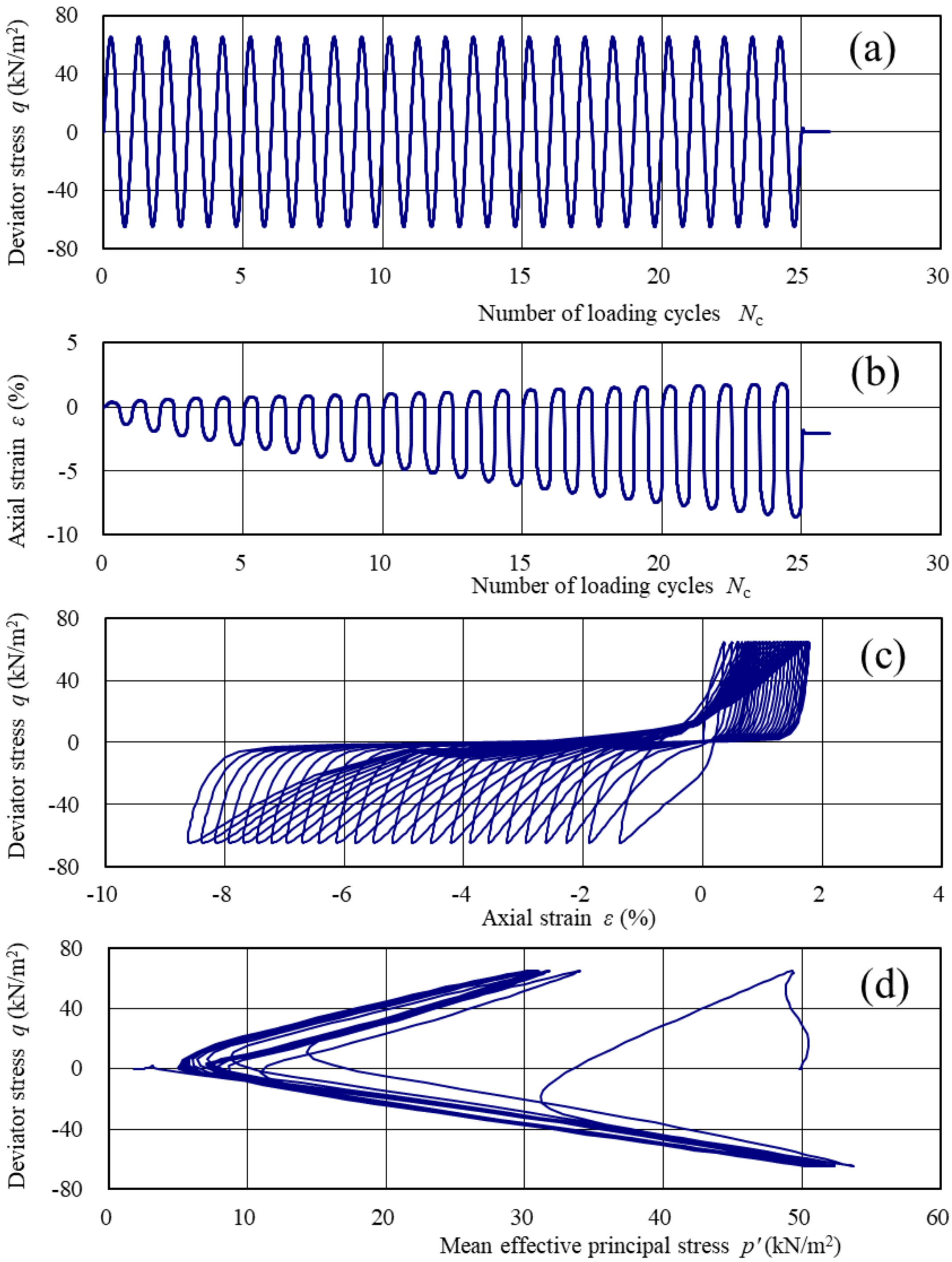

Figure 4. Test result of (1) F45O100

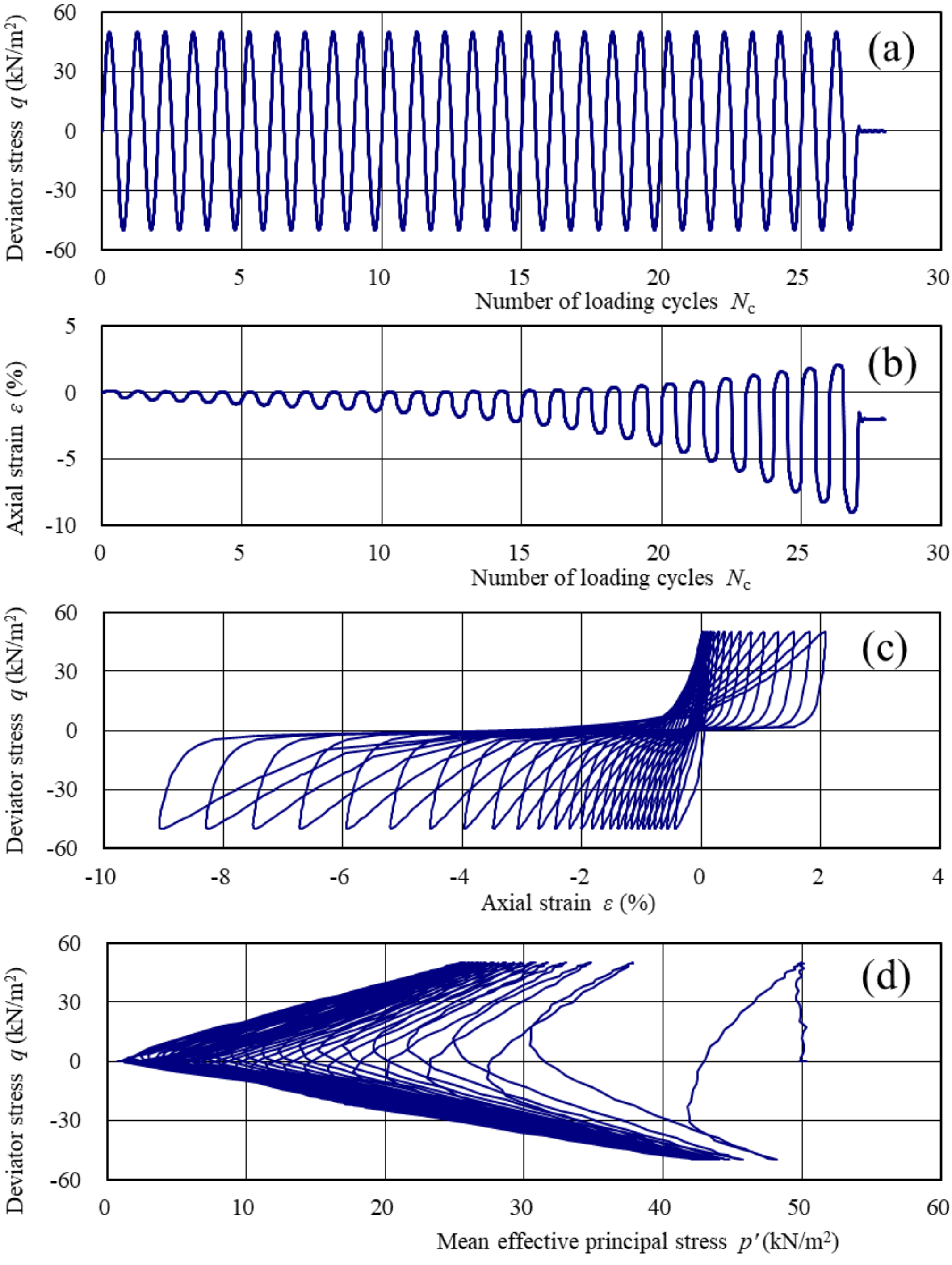

Figure 5. Test result of (5) F45O95

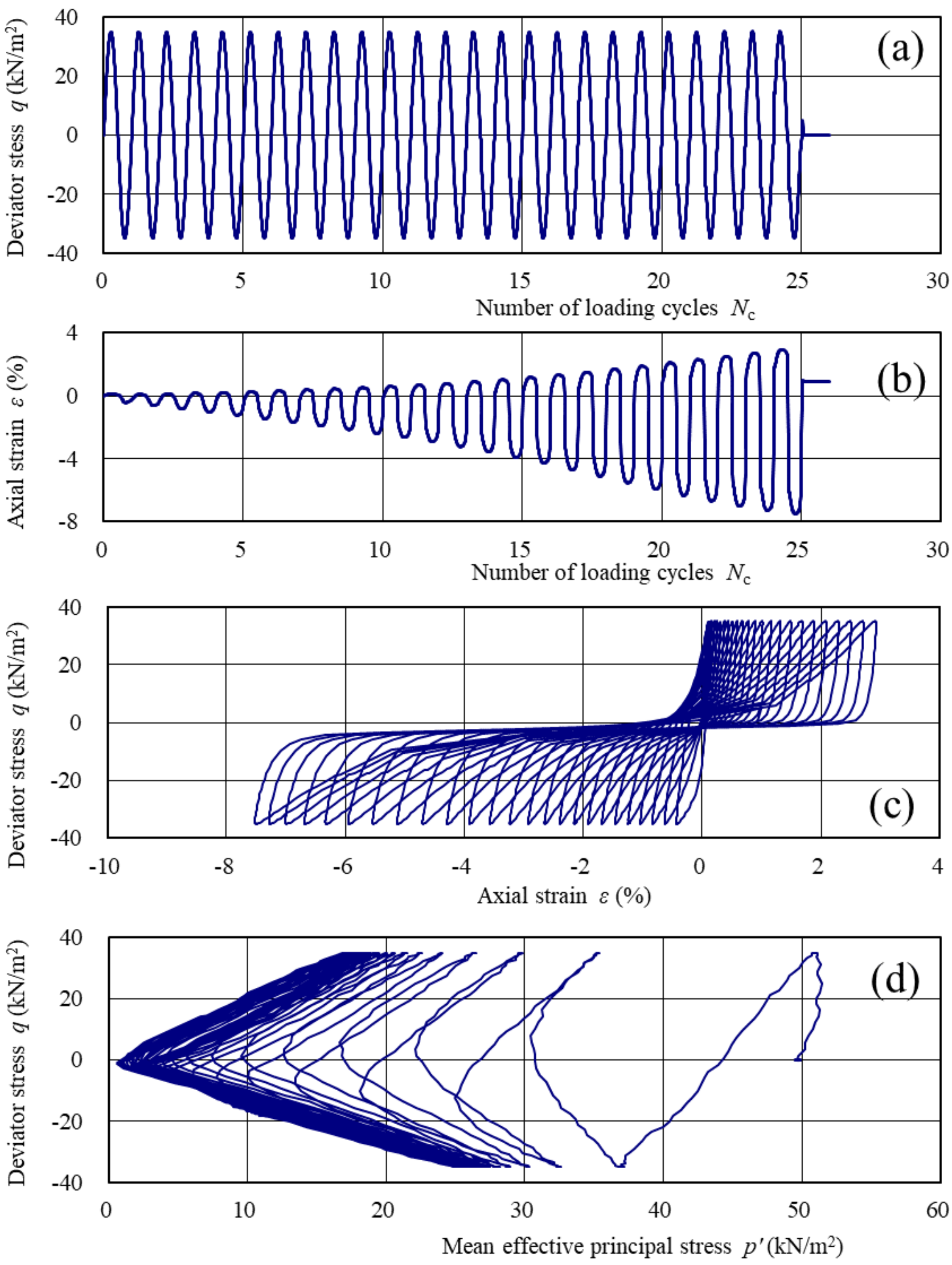

Figure 6. Test result of (6) F45W95

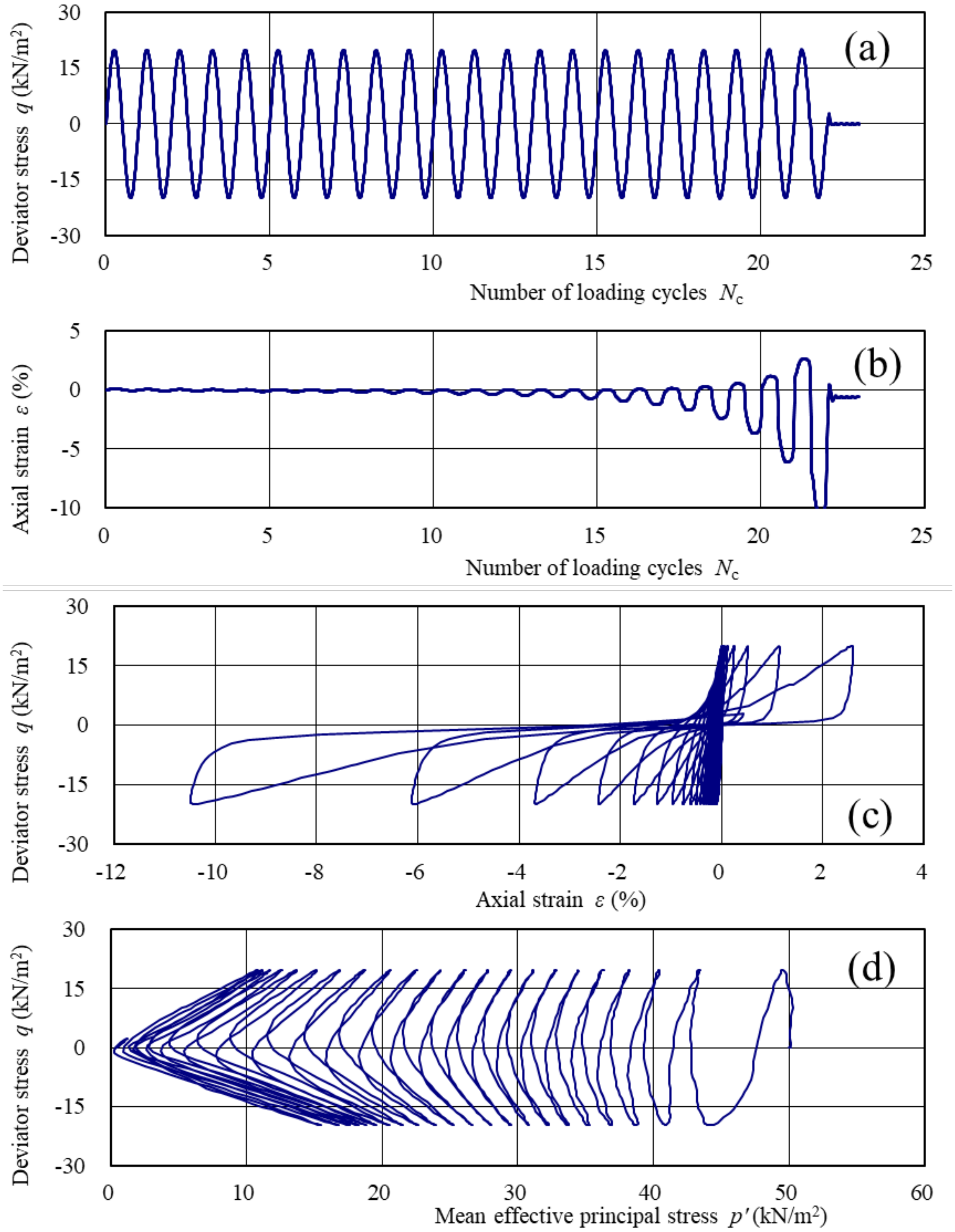

Figure 7. Test result of (3) F45D95

The strain amplitudes observed for (1) F45O100 and (6) F45W95, which were prepared at a high degree of saturation in densely compacted state, increased gradually by almost the same increment for each loading cycle. However, the effective stress path indicated almost liquefied state by only the first several loading cycles before double amplitude strain increased to 5%. It can be seen that because of the densely packed state, even if the effective stress is almost liquefied due to the generation of excess pore water pressure, there is tenacity against deformation.

On the other hand, in the densely packed case (5) F45D95 and the slightly loosely packed case (3) F45D90, which have a lower degree of saturation at compaction, the rigidity was maintained while the number of loading cycles was small, and then the strain amplitude suddenly increased significantly to reach liquefaction. This suggests that it lacks tenacity against liquefaction, and even if the liquefaction resistance R_{L20} is the same as in (1) F45O100 and (5) F45D95, indicating that the tenacity which does not appear in the index such as R_{L20} is very important to evaluate the performance of liquefaction resistance.

5. Conclusions

In the pumice sand (volcanic ash sand) collected from the earth fill at Satozuka District in the City of Sapporo, Japan, with a large amount of non-plastic fines examined in this study, the liquefaction resistance R_{L20} can be expected to be only about 0.2 at a degree of compaction of 90%, but if the soil is densified by compaction at a degree of compaction of 95% or more, the liquefaction resistance R_{L20} can be expected to be more than 0.3. Densification by compaction is required to increase liquefaction resistance. In addition, the skeletal structure is also important even at the same dry density (i.e., degree of compaction), and a higher liquefaction resistance can be expected under the compaction conditions on a dryer condition in water content at compaction. On the other hand, the tenacity for deformation in liquefaction under cyclic loading may be lost in the compaction conditions on the dryer condition, so the tenacity for liquefaction should also be noted.

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Тығыздау жағдайларының пластикалық емес ұсақ фракциясы бар пемза құмының сұйылту сипаттамаларына әсері

Аңдатпа. Бұл зерттеу пемза құмының сұйылту сипаттамаларын зерттеп, тығыздау жағдайларымен байланысына ерекше назар аударды. Осы зерттеу нәтижесінде алынған жаңа нәтижелер келесідей қорытындыланады. Пластикалық емес бөлшектері көп пемза құмында R_{L20} сұйылтуға төзімділігі 90% тығыздау дәрежесінде шамамен 0,2 болады деп күтуге болады, бірақ егер топырақ 95% немесе одан да көп тығыздау дәрежесіне дейін тығыздалса, оны 0,3 немесе одан да көпке дейін арттыруға болады. Сонымен қатар, рамалық құрылым құрғақ болған кезде де бірдей тығыздықта да маңызды және тығыздау кезінде су болған кезде тығыздау жағдайында жоғары сұйылтуға төзімділікті күтуге болады. Екінші жағынан, циклдік жүктеме кезінде сұйылту кезінде деформацияға төзімділік кептіргіште тығыздау жағдайында жоғалуы мүмкін, сондықтан сұйылтуға төзімділікті де ескеру қажет.

Түйін сөздер: пемза құмы, жанартау құмы, пластикалық емес бөлшектер, сұйылту, тығыздау шарты, үш осьті циклдік жүктемені сынау.

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Влияние условий уплотнения на характеристики разжижения пемзового песка с непластичной мелкой фракцией

Аннотация. В этом исследовании были рассмотрены характеристики разжижения пемзового песка, уделяя особое внимание взаимосвязи с условиями уплотнения. Новые результаты, полученные в ходе этого исследования, резюмируются следующим образом. В пемзовом песке с большим количеством непластичных частиц можно ожидать, что сопротивление разжижению R_{L20} составит всего около 0,2 при степени уплотнения 90%, однако оно может быть увеличено до 0,3 или более, если грунт уплотняется путем уплотнения до степени уплотнения 95% или больше. Кроме того, каркасная структура также важна даже при той же плотности в сухом состоянии, и можно ожидать более высокой стойкости к разжижению в условиях уплотнения в более сухом состоянии при содержании воды при уплотнении. С другой стороны, устойчивость к деформации при сжижении при циклической нагрузке может быть утрачена в условиях уплотнения в сушилке, поэтому также следует учитывать устойчивость к сжижению.

Ключевые слова: песок из пемзы, вулканический песок, непластиковые частицы, сжижение, условие уплотнения, испытание на трехосную циклическую нагрузку.

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