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A MICRO-BUBBLE INJECTION METHOD FOR A COUNTERMEASURE AGAINST LIQUEFACTION

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ABSTRACT

A micro-bubble is an independent bubble of 10~100μm in diameter. A soil improvement method injecting the micro-bubbles into ground was newly developed, which may provide a cost-effective and simple countermeasure method against soil liquefaction. Although it is well known that soil resistance to liquefaction increases as the saturation degree of the soil decreases, it has been difficult to lower the saturation degree of ground homogeneously. A technique using micro-bubbles, however, can be expected to solve the problem because the micro-bubbles can easily permeate into voids among sand particles.
A series of column tests for saturated sand injected with water mixed with micro-bubbles was conducted. Based on these test results, factors influencing on decreasing the saturation degree of ground were examined and the feasibility of the micro-bubble injection method was studied in this paper.

Keywords: Soil liquefaction, Micro-bubble, Saturation, Liquefaction strength

INTRODUCTION

Soil liquefaction is still a serious problem on disaster prevention for countries frequently attacked by earthquakes, such as Japan. Especially, if sea walls and levees on sea shores and rivers would be collapsed by soil liquefaction caused by an earthquake, the following tsunami may cause devastated inundation. Although the risk of such a disaster should be diminished as soon as possible, enormous cost and time of liquefaction countermeasure for these seawalls and levees are hindering early improvement to them.

It is well known that liquefaction resistance of a soil increases with decreasing the saturation degree of the soil (Yoshimi et al.1988), and the decreased saturation degree of ground can prevent seismic damage of infrastructures. Shiraishi (1997) reported that 312 examples of structures having pneumatic caisson foundation were prevented from fatal damage by liquefaction in KOBE earthquake and in NIGATA, because the ground surrounding the foundation was unsaturated by air entrapped during the construction. Okamura et al. (2006) conducted laboratory tests on specimens taken from six sites where the foundation grounds had been improved with sand compaction pile. The results showed the saturation degrees of the soils measured after several decades from the construction were as high as those measured immediately. It indicated that, in the sand compaction pile method, there was the effect of decreasing the saturation degree of ground in addition to the densification of surrounding ground.

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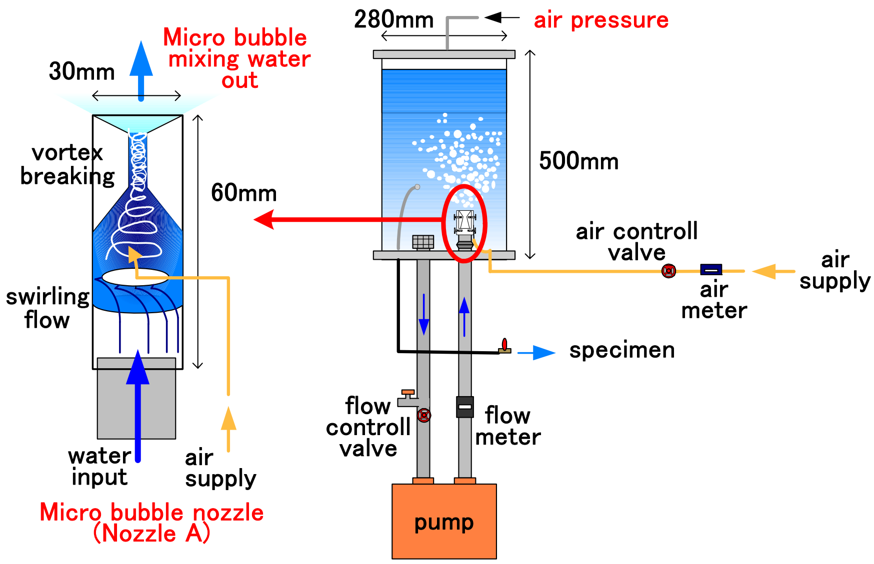

Figure 1. The micro-bubble generator

It is, however, difficult to lower the saturation degree of ground homogeneously because air injected into ground tends to move upward and make an air way easily. Micro bubbles were, therefore, used as a technique to lower the saturation degree of ground easily in this research. As the micro-bubble is an independent small bubble of 10~100μm in diameter, it can easily permeate voids among sand particles. In this paper, the feasibility of the micro-bubble injection method proposed was examined by conducting a series of laboratory column tests.

EXPERIMENTAL METHODOLOGY

Micro bubble generator

A micro bubble generator used is shown in Figure 1. It consists of an acrylic cell with 280mm in diameter and 500mm tall, a micro bubble nozzle and a water pump. The micro-bubble nozzle, named Nozzle A, developed by Abe et al.(2005), can make micro bubbles by using vortex breaking. Air supply to the nozzle was controlled by an air valve and set at air inflow of 2 lit./min in this research. An average diameter of the generated micro-bubbles was estimated by the Navier - Stokes equation to be about 30μm at normal atmospheric pressure because the measured rise velocity of the micro bubbles in a watered cell ranged between 70 and 900μm/sec. The water pump used was a high-lift pump with maximum flow pressure of 500kPa and maximum flow capacity of 28m/min. The flow and water pressure of the pump were adjusted by a flow control valve.

In the beginning of the test, it was tried to directly inject the mixture of water and micro bubbles made by this generator into a sand specimen. In this way, however, there was found a fault that the injected micro bubbles were expanded within a tube connected to the sand specimen. Hence, this generator was mainly used to make air-supersaturated water under 400kPa of pressure, and another smaller micro bubble nozzle, named Nozzle B, was set immediately before the first column. This method consequently gave good results that the air-supersaturated water could be easily stored for a long time if it remained under the pressure and it also heightened the concentration of the micro bubble generated.

Micro-bubble injection test

A schematic view of micro bubble injection test is shown in Figure 2. In the test, the micro bubbles re-precipitated from the air-supersaturated water by the nozzle B were injected into three consecutive columns, each of which column had 74mm in diameter and 300mm tall. A sand specimen was prepared by air-pluviating Toyoura sand in the column, in which relative density of about 60% and initial saturation degree of 100% were targeted. The physical properties of Toyoura sand are shown in

Table 1. In each column, the degree of saturation for the sand specimen was required by measuring the weight change of the column with a load cell, and the pore water pressure in the columns was measured by pressure gages. During injection, concentration of dissolved oxygen (DO) was continuously measured with water drained from the column 3 by a DO meter. Initial DO concentrations in the air-supersaturated water made by the micro bubble generator and in the mixture of water and micro bubbles precipitated by the nozzle B were also measured under the normal atmospheric pressure, respectively.

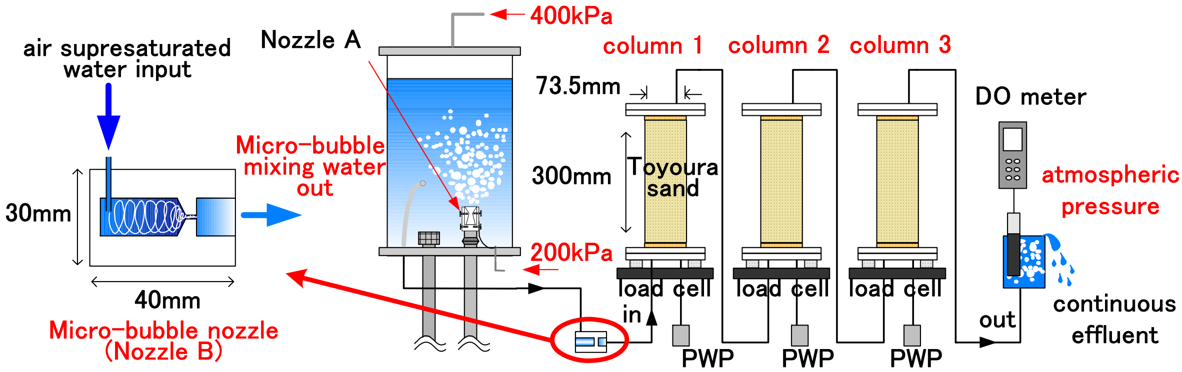

Figure 2. Micro-bubble injection test

Table 1. The physical propertis of Toyoura sand

ρ_s	2.640g/cm^3
e_{max}	0.973
e_{min}	0.609

Table 2. Test case and specifications

CASE	Type of injection	Column1		Column2		Column3	
		Dr(%)	V_v (cm^3)	Dr(%)	V_v (cm^3)	Dr(%)	V_v (cm^3)
Case1	Air	75	541	75	541	71	551
Case2	Air supersaturated water	62	526	60	556	59	536
Case3	Micro-bubble mixing water	60	533	59	534	58	500

Table 3. The mixed ratio between the silt and sand

CASE	Volume ratio	
	Toyoura sand	silt
Case1	100%	0%
Case2	100%	0%
Case3	20%	80%
Case4	50%	50%

The saturation degree of the sand specimen, S_r, was calculated by substituting the measured weight m_W in the following equation,

$$S_r = S_{r0} - \frac{(V_{W0} - V_W)}{V_V} \times 100 = S_{r0} - \frac{(m_{W0} - m_W)}{m_{W0}} \times 100 \qquad (1)$$

where V_v is a total volume of void in the specimen and the subscript 'o' means an initial value of each parameter.

Two kinds of tests injecting the air and the air-supersaturated water into the specimens were conducted to compare with the case of the mixture of water and micro bubble. These test conditions are summarized in Table 2.

The micro bubble injection test was also conducted for two kinds of silty sand specimens. In these tests, one column was used because of the high seepage resistance of the silty sand specimen. The silt used is an artificial crushed silica with the average diameter of 70μm. The test condition and the mixed ratio between the silt and the sand are shown in Table 3.

Air volume controlled test

An air volume controlled test was performed for each column after completing the injection in order to confirm the saturation degree of the column and investigate the characteristics of the micro bubble contracting and expanding in a soil. The test layout is shown in Figure 3. In the test, as a piston with 5cm of a diameter was pushed up into a cylinder by a motor at a given constant rate, water in the cylinder was forcibly conveyed to the column. The volume of the conveyed water and the pore water pressure in the column were measured by a displacement sensor and a pressure gage, respectively. The test data were analyzed by using the relationship between the pressure and the air volume, which was derived from Boyle's law and the definition of the saturation degree of a soil, as follows.

$$\Delta V = V_a - \frac{P_0 V_a}{P_0 + \Delta P} \qquad (2)$$

$$S_{r0} = \frac{(V_v - V_a)}{V_v} \times 100 \qquad (3)$$

where V_a is an initial air volume in a column and P_0 is an initial absolute pressure. ΔV is a volume change decreased by applied pressure increment ΔP. S_{r0} and V_v are an initial saturation degree and a total volume of void in the specimen, respectively. From the equation (2), it is clarified that the volume change ΔV is linear with the inverse of the applied absolute pressure, $P_0 + \Delta P$, and the initial air volume V_a is given as the volume change at which the infinite absolute pressure is applied.

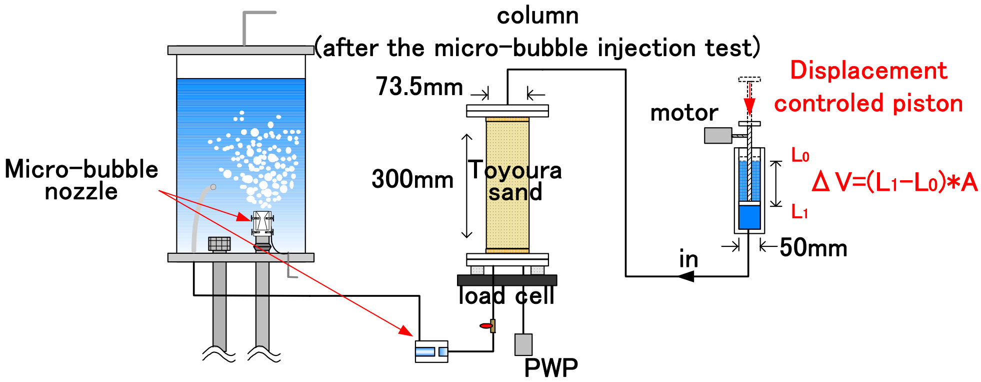

Figure 3. Air volume controller

Liquefaction resistance test

A series of cyclic triaxial compression tests, named liquefaction resistance tests, was conducted for sand specimens injected with the mixture of water and micro-bubble. The specimens of Toyoura sand with 50mm in diameter and 100mm tall were prepared at relative density of about 60%, which were saturated by injecting de-aired water after inflow of CO_2 gas. After the specimen was consolidated under an isotropic confining stress of 196kPa and a buck pressure of 98 kPa, the mixture of water and micro bubble produced through the nozzle B was injected in the specimen until the saturated degree of the specimen reached the prescribed saturation degree of 80%. The saturation degree of the specimen was obtained by using a double pipe installed in the triaxial apparatus and measuring the volume change of water introduced into the specimen by applying a pressure. The liquefaction resistance test was performed by applying a sinusoidal loading of a constant load amplitude at a frequency of 0.2 Hz.

THE TEST RESULT AND DISCUSSION

Distribution of diameter of micro bubbles generated

Figure 4 shows a distribution of the diameter of the bubbles generated by the nozzle B. As it is known that there is a linear relationship in logarithm scale between the diameter of a micro bubble and a rise rate of the micro bubble in water and the relationship can be derived from Navier-Stokes equation (Ohnari, 2003), the diameter of a micro bubble was estimated from the rise rate of the micro bubble measured by visual observation. The diameter of the micro bubble obtained ranged from 10 μm to 100 μm at the average of 30 μm.

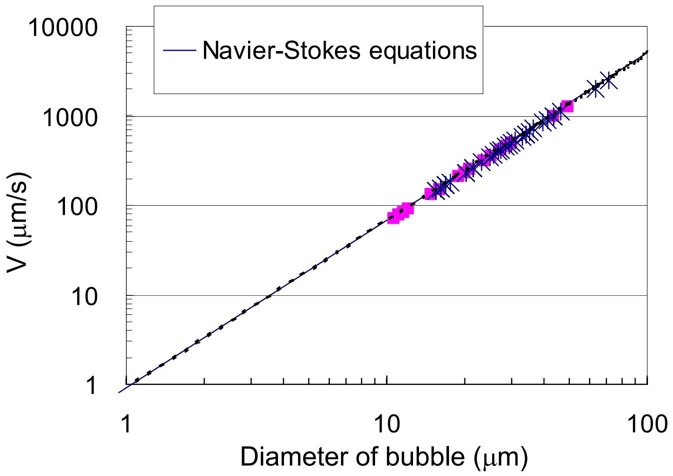

Figure 4. Distribution of diameter of bubbles estimated from a rise velocity

Micro bubble injection tests into sand specimen

Figure 5 shows the relationships between the saturation degree of the specimen and the total drain water volume in the air injection test, where the pressure applied to inject air into the specimens was 20kPa.

In Figure 6, it was observed that the saturation degree of the specimen in the column 1 decreased rapidly as an air surface gradually proceeded. Once the air surface came at the column 2, the saturation degree in the column 2 began to decrease instead of the decrease in the column 1. Thus, it seems that the progression of the air surface produced the decrease of the saturation degree for the air injection. For all columns, the decreases of the saturation degree were restrained at the almost same value of 70-75%. As air bubbles seen at the internal surface of the columns were streaky, it was thought that some air ways in the specimens were formed. For this reason, it was suggested that de-saturation by the air injection was not so effective to make ground homogeneously de-saturated.

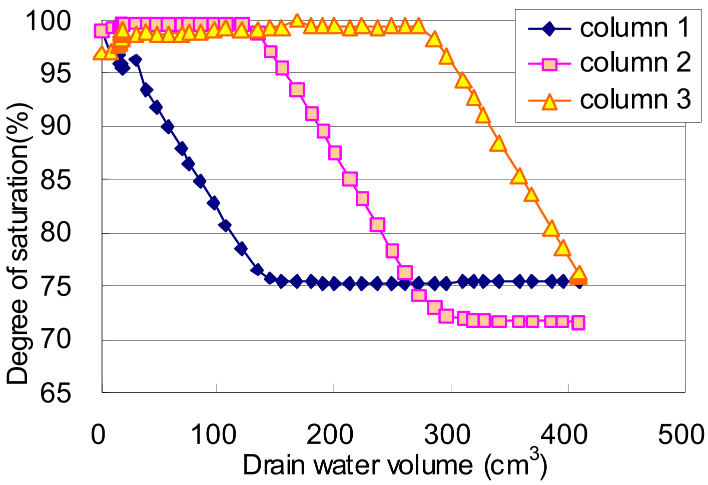

Figure 5 Effect of air injected into the specimens on degree of saturation, respectively

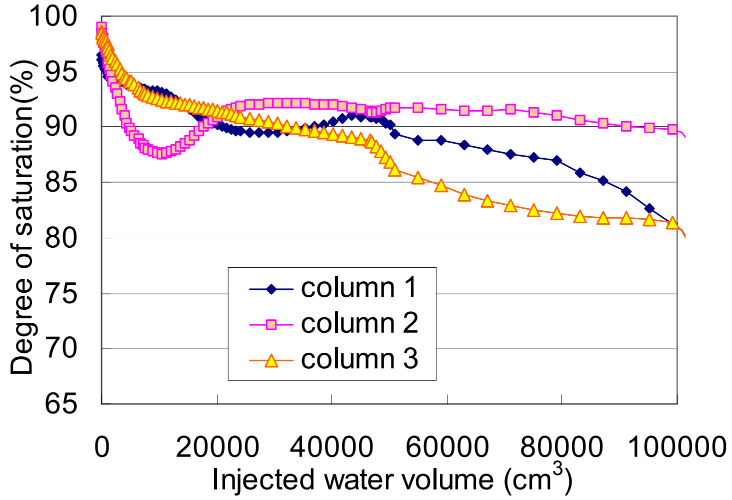

Figure 6 Effect of air-supersaturated water injected into the specimens on degree of saturation, respectively

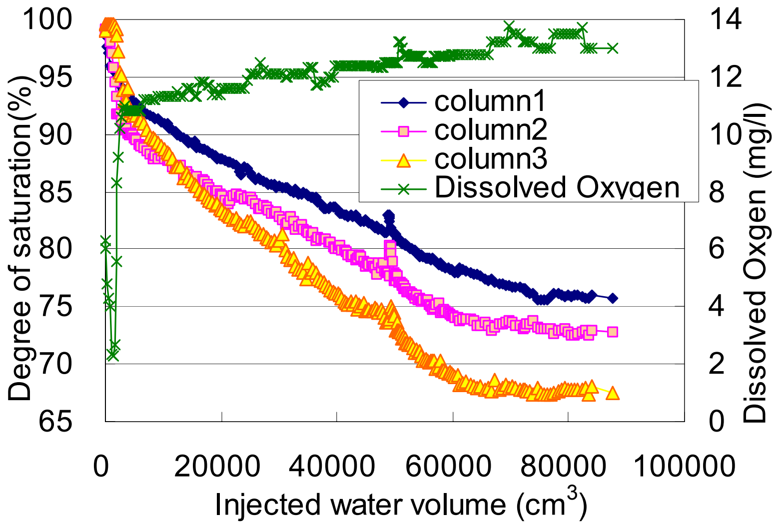

Figure 7 Effect of Micro-bubble mixing water injected into the specimens on degree of saturation and change in dissolved oxygen

As seen in Figure 6, injecting the air-supersaturated water could decrease the saturation degree of the specimens. However, the injected water volume required for decreasing the saturation degree of the specimens until 80% was quite large as compared with the case of the air injection. For the case of injecting the mixture of water and micro bubble shown in Figure 7, although the injected water volume required was somewhat large, the obtained saturation degree became lower than that by the air injection. In addition, the saturation degrees of all specimens in this case began to decrease at almost the same time. The curve of concentration of dissolved oxygen measured with the drained water is also included in Figure 7, where the DO value of the drained water gradually increased with water volume injected. In the case of the micro bubble injection, it was thought from these results that micro bubbles trapped in the specimen were expanded with the supply of air from the subsequent water flow and/or micro bubbles were gradually re-generated by the subsequent water flow and trapped in the specimen. As compared with the other cases, the micro bubble injection method is recommended as the method of de-saturating ground because of decreasing the saturation degree of ground homogeneously and continuously.

Figure 8 and 9 show the change in pore water pressure and the calculated coefficient of permeability in the case 3, respectively. As the injected water volume increased, the pore water pressure slowly increased and the coefficient of permeability obtained gradually decreased. These results came from that the air bubbles trapped in the specimens interfered the water flow. If the saturation degree required for the liquefaction countermeasure is 80% at least, the reduction by half of the permeability coefficient will give no problem.

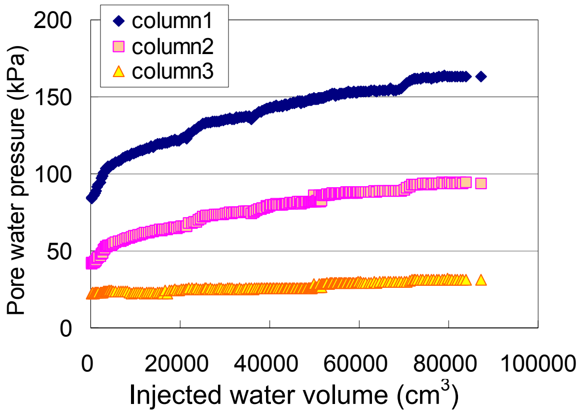

Figure 8 Change in pore water pressure in the case of injecting the mixture of water and micro bubble and injected water volume, respectively

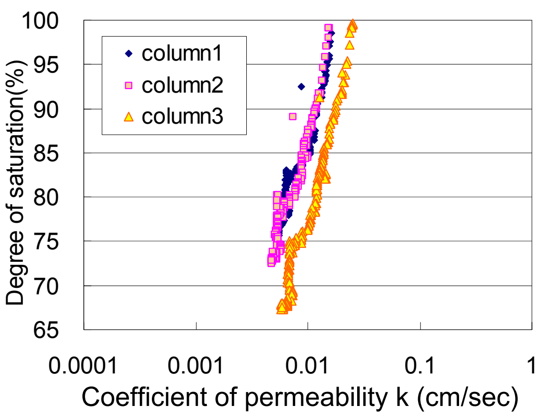

Figure 9 Relationships of degree of saturation with coefficient of permeability in the case of injecting the mixture of water and micro bubble, respectively

Micro bubble injection tests into silty soils

In order to evaluate the applicability of the micro bubble injection method, a series of micro bubble injection tests was conducted for silty soils. In these tests, only one column was used instead of three consecutive columns shown in Figure 2. Figure 10 shows the relationships between the saturation degree of the specimen and the injected water volume for 4 cases, including 2 cases of the mixture of silt and sand. For the cases of the silt mixtures, although the specimens couldn't be fully saturated because of their low permeability, their variations of the saturation degree decreased were comparable with that of the sand injected micro bubble. While a lot of time was needed to sufficiently inject the mixed water because the permeability coefficients of the silt mixtures were one tenth of the sand's, the saturation degrees of both cases finally reached 85%. Although the reduction of injection time is a requisite, it seems that the micro bubble injection method has potential application even for silty ground.

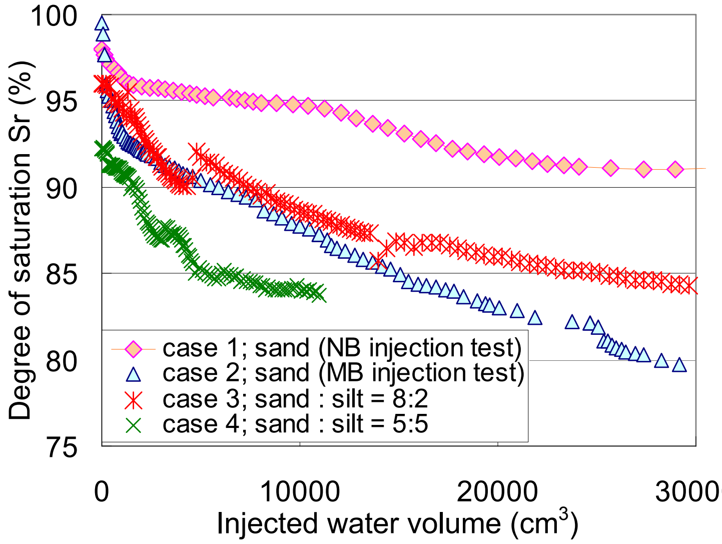

Figure 10 Effect of mixture water and micro bubble injected into the different kind of specimens on degree of saturation

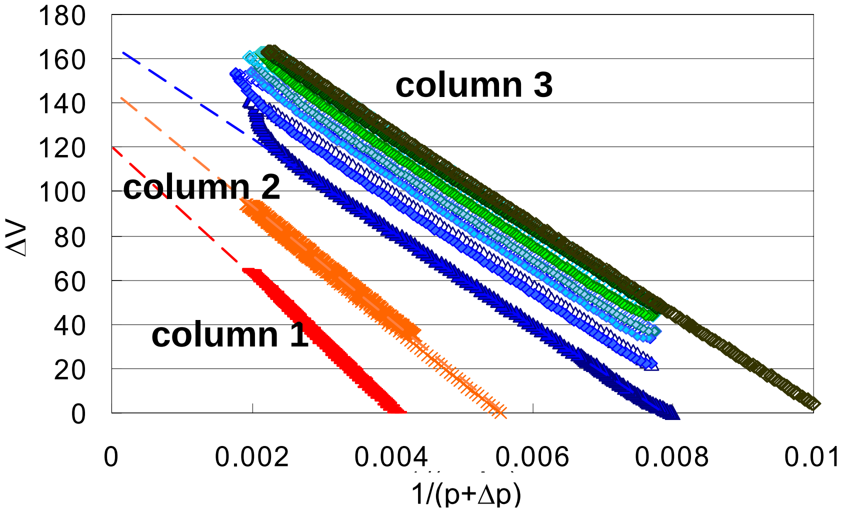

Figure 11 Observed ΔV in repeated tests of compression and decompression using the air volume controlled equipment and 1/(p+Δp)

Table 4. Comparative tables between Sr observed by air volume controlled test and Sr measured by change in column weight

	column 1	column 2	column 3
Pore water pressure after the test (kPa)	163	94	31
ΔV observed by air volume controlled test (cm^3)	125	145	168
Sr observed by the air volume controlled test (%)	76.5	72.8	66.4
Sr measured by change in column weight (%)	76.2	73.1	67.5

Air volume controlled test

The law of ideal gas shows that the product of the volume of a gas and its absolute pressure over the absolute temperature becomes a constant. However, it has not been confirmed yet whether a micro bubble in soil showed the same responses. Thus, cyclic tests of compression and decompression using the air volume controlled equipment were conducted for the injected specimens. The test result for the micro bubble injection is shown in Fig.11. From this figure, it was confirmed that in all columns, except for the column 3 shown in Figure 11, the volume change ΔV was linear with the inverse of the absolute pressure, $p+\Delta p$, which means the micro bubble in soil behaves under the law of ideal gas. In the case of the column 3, however, the volume change measured at the range of high absolute pressure became larger than that predicted by the gas law and hysteresis curves were observed. It seems that the hysteresis were caused by re-dissolution of the micro bubbles under the applied high pressure, with obeying Henry's law for dissolved gas. However, because more than 400 kPa of pore water pressure will not be applied to micro bubbles used for liquefaction countermeasure, there may be no need for worrying about the micro bubbles re-dissolving.

The result shown in Figure 11 can be also used to calculate the saturation degree of a specimen, because an intercept of the volume change axis shows an air volume involved in the specimen at the initial pressure. The intercepts in Figure 11 were compared with the final values of the volume change obtained from the measurement of column weight in Table 4. In the results, both of calculated values showed good agreements in each other. It was, therefore, concluded that, in order to measure the saturation degree of soil mass, the method using the air volume controlled equipment was more accurate as compared with a manner using a burette because of no air bubble leaking from the column during the test.

Mechanisms of micro bubble de-saturating soil specimen

From the results mentioned above, the mechanism of de-saturation by injecting the mixture of water and micro bubble in the specimen was to some extent clarified. In this section, it will be discussed how concentration of air dissolved in the generator is consumed in the process of flow up to the drain. Figures 12 to 14 illustrate the transition of the concentration distributions of dissolved air from the generator to the drain through the nozzle B and the three columns. In the figures, the concentration distributions of precipitated air trapped in the specimens are also included. The weight concentrations of dissolved air at the generator and at the nozzle B were derived from the initial values of DO measured at the same locations. The conversion of the measured DO concentration to the predicted concentration of dissolved air was done by using the conversion ratio, 1.666, proposed by McNeil C. L.(2006). The weight concentration of precipitated air which was trapped in the specimens was obtained from the rate of decreasing the saturation degree for each specimen. Supposing that the sum of the concentrations of the dissolved air and the precipitated air is kept constant with the initial concentration at the generator during the process, the deduced concentration of the dissolved air might equal the concentration of the precipitated bubbles being carried by the water flow.

At the early stage of de-saturation, most of air bubbles precipitated by the nozzle B were trapped in the specimens as seen in Figure 12, and therefore the saturation degree of the specimens rapidly decreased. The concentration of the dissolved air at the drain became somewhat lower than that at the nozzle B. At the middle stage shown in Figure 13, the concentration of bubbles trapped was decreased and most of bubbles precipitated were eliminated from the columns with the drained water. At the final stage shown in Figure 14 where the decrease of the saturation degree in all columns moderated, the mixture of supersaturated water and micro bubble generated by the nozzle B was kept almost intact and passed out of the columns. The results mean that there exists a limit of the saturation degree decreased by the micro bubble injection method. On the other hand, the existence of such a limit indicates that the area improved by this method will be expanded sequentially because the dissolved air in the water flow is not consumed in the area where the saturation degree reaches to their limit.

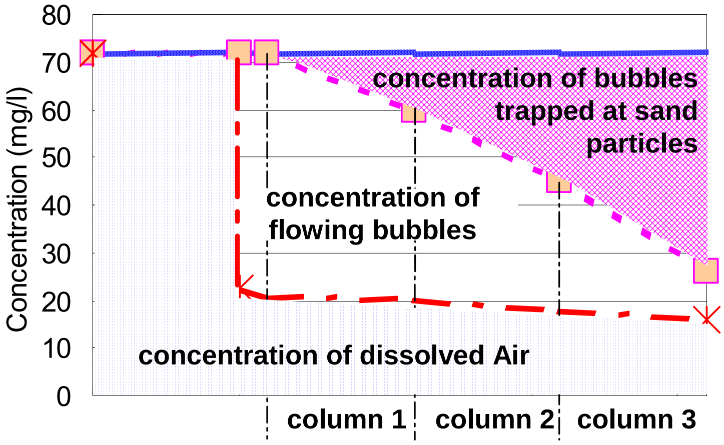

Figure 12 Illustration of transition of the concentration distributions of dissolved air through the nozzle B and the three columns at the early stage

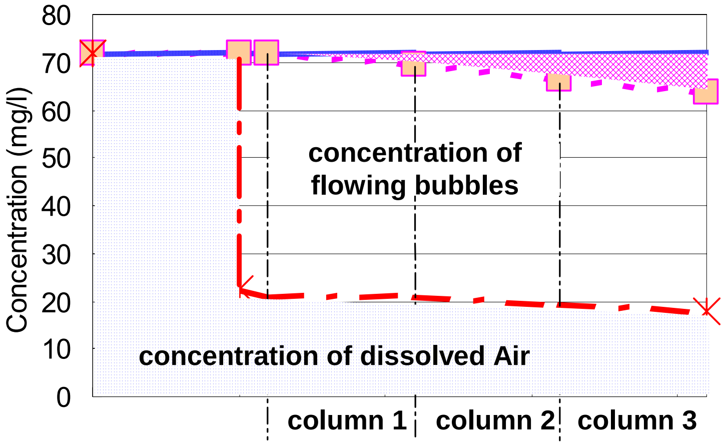

Figure 13 Illustration of transition of the concentration distributions of dissolved air through the nozzle B and the three columns at the middle stage

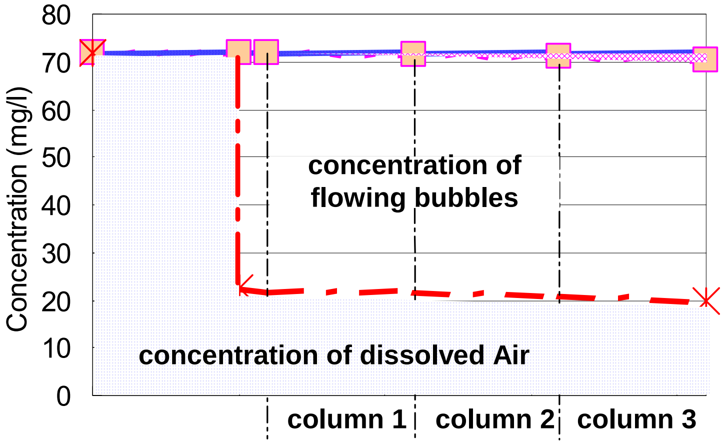

Figure 14 Illustration of transition of the concentration distributions of dissolved air through the nozzle B and the three columns at the final stage

Liquefaction resistance test

In this test, the cyclic stress ratio to cause the double amplitude axial strain, DA, of 5% in 15 cycles is defined as the liquefaction resistance. Figure 15 shows the results of triaxial cyclic loading test for the saturated sand specimen and for the sand specimen unsaturated to 90% of Sr by the injection of the micro bubble mixture. As a summary of these test results, the relationships between the cyclic stress ratio and the number of cycles N_c to cause DA of 5% are shown in Figure 16. In this figure, test results done by other researchers (Yoshimi et al.1989, Okamura et al.2006) are also described, where the tests were conducted for the loose sand specimens. It seems that as the degree of saturation of the specimen decreased, the cyclic stress ratio increased irrespective of number of cycles. Liquefaction resistance ratio, which is defined as the liquefaction resistance of partially saturated sand normalized with respect to that of fully saturated sand, is plotted against the degree of saturation in Figure 17. From the figure, It was seen that the cyclic resistance of the specimen de-saturated by injecting micro bubble, in which the degree of saturation was 80 % and the relative density was 60%, was 1.7 times larger than that of the saturated sand. Thus, the effect of improvement by injecting micro bubble was confirmed. This liquefaction resistance, however, was obviously lower than the value shown by Yoshimi et al. (1989). As all of tests with 80% of the saturation degree were terminated with necking failure of the specimens, it was thought that axial strain reached DA of 5% due to not liquefaction but extension caused by necking failure. Okamura et al. (2006) conducted a series of cyclic undrained triaxial tests for the specimens injected air bubble, where the relative density of the specimens was 40% and the saturation degree was 80%. It was also reported that in the specimens there were not seen the necking failure because of their small relative density. The liquefaction resistance ratios plotted in Figure 17 were very close to the value by Yoshimi et al. The liquefaction resistance ratio for the specimen injected micro bubble might be greater than what it was.

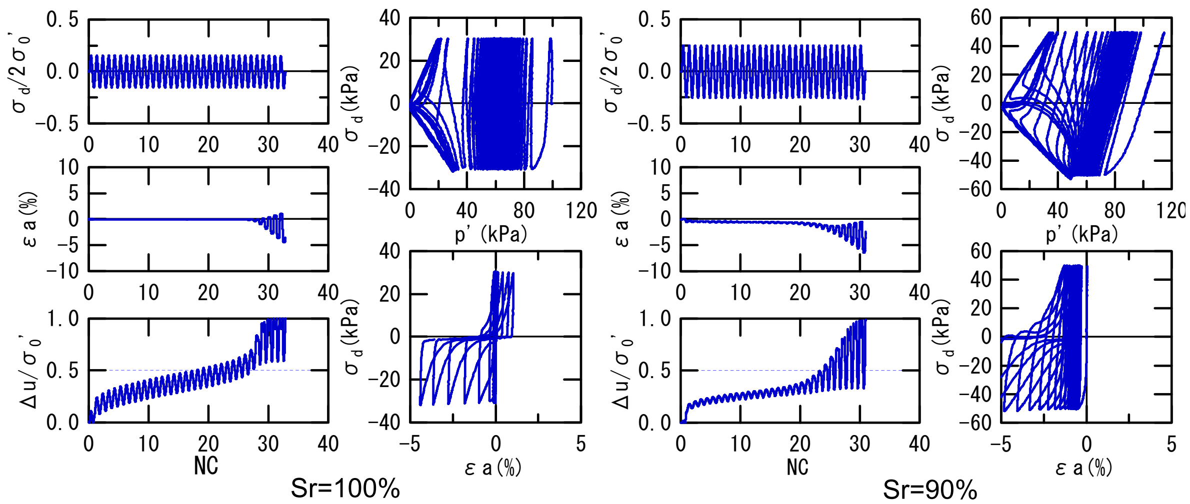

Figure 15 Results of cyclic triaxial test

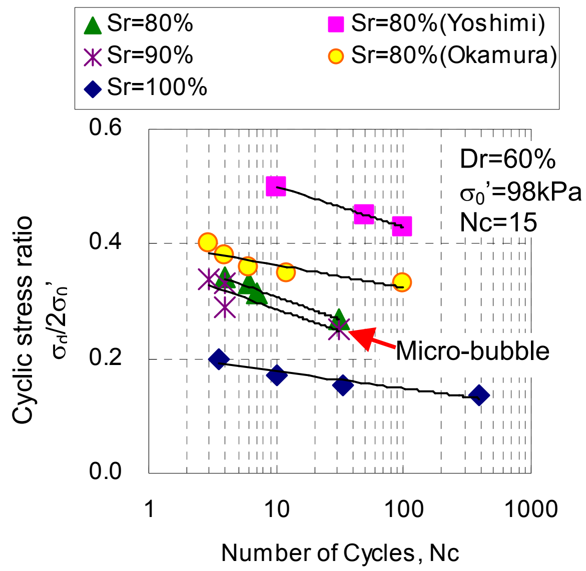

Figure 16. Relationship between cyclic stress ratio and number of cycles

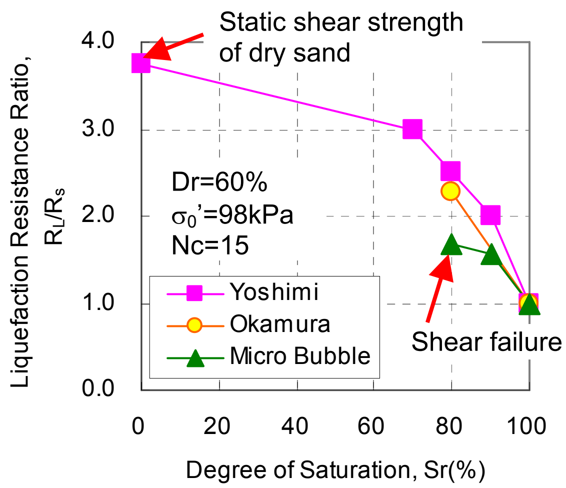

Figure 17. Results of tests on the effect of degree of saturation on liquefaction resistance

CONCLUSIONS

In this paper, the feasibility of the micro bubble injection method proposed was examined by conducting a series of laboratory column tests. The conclusions obtained are as follows.

1. After the micro bubble injection tests, the decrease of saturation degree S_r of the micro bubble injected sand specimens were restrained at over 75-percent. The degree of saturation S_r depended on the pore water pressure, and S_r increased with decreasing of pore water pressure.
2. It is thought that de-saturation by the air injection was not so effective to make ground homogeneously. It's a disadvantage that some air ways in specimens were formed.
3. While a lot of time was needed to sufficiently inject the mixed water because the permeability coefficients of the silt mixtures were one tenth of the sand's, the saturation degrees for both cases finally reached 85%. Although reduction of time for injecting is requisite, it seems that the micro bubble injection method has potential application for silty ground.
4. As a result of air volume controlled test, it seems that the hysteresis of volume change were caused by re-dissolution of micro bubbles with applied high pressure as Henry's law shows. However, as more than 400 kPa of pore water pressure would not be put on micro bubbles used for liquefaction countermeasure, there may be no need for worrying about the micro bubbles re-dissolving.
5. There exists a limit of the saturation degree decreased by the micro bubble injection method. On the other hand, it can be pointed out that the existence of the limit enables area improved by this method to be expanded sequentially.
6. The cyclic resistance of the specimen de-saturated by injecting micro bubble, in which the degree of saturation was 80 % and the relative density was 60%, was 1.7 times larger than that of the saturated sand. Thus, the effect of improvement by injecting micro bubble was confirmed.

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