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A Feasibility Study of Dewatering and Recovering as a Liquefaction Countermeasure for Existing Residential Areas

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ABSTRACT: The 2011 Tohoku Earthquake caused extensive liquefaction damage over a wide area. Mihama-ku of Chiba City is one of the heavily affected areas. The local government decided to apply dewatering to one of these areas. This method, however, is not appropriate for the areas where there are no clayey layers that can be used as a cut-off layer. A combined process of lowering and subsequent restoring the groundwater level can be used as an alternative. This process is believed to create an unsaturated soil layer that is liquefaction resistant. The authors have conducted centrifuge shaking table tests in order to examine this idea by building a special test apparatus for this purpose. From the tests, it was found that the lowering and recovering process actually creates a layer of unsaturated soil and the thickness of liquefied soil is greatly decreased because of this process. In addition to the laboratory tests, the authors have conducted various in-situ soil investigations including measurement of degree of saturation during a field demonstration experiment of dewatering. It was confirmed from the tests that the lowering and recovering process of groundwater can create a layer of unsaturated soil also in an actual ground.

1 INTRODUCTION

The 2011 Tohoku Earthquake with the magnitude of 9.0 that struck eastern Japan on March 11 caused extensive liquefaction-induced damage over a wide area especially along the coast of Tokyo Bay. Mihama-ku (Mihama Ward) of Chiba City, located east of Tokyo, is one of the heavily affected areas. This ward consists entirely of reclaimed ground and reclamation was done by hydraulic filling of dredged soils taken from the sea bed at the time of reclamation. Liquefaction-induced damage was so severe in the residential area that significant subsidence and tilting due to liquefaction caused health disturbance. Figure 1 shows the distribution of liquefaction-induced damage in the form of 50 m square grid (Sekiguchi et al. 2012). As can be seen in the figure, severe damage was observed throughout entire Mihama-ku. In reaction to this extensive liquefaction damage, the local government decided to apply dewatering to one of the heavily affected areas (target area in Figure 1) as a countermeasure and conducted a demonstration experiment. However, this method requires a shield wall that surrounds the target area and a low permeability clayey stratum underneath a liquefiable sandy layer.

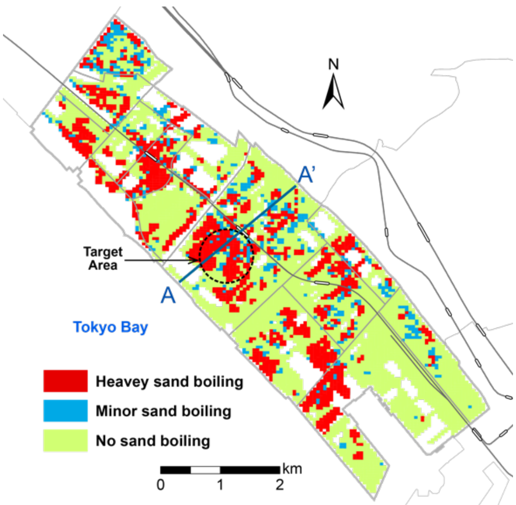


Figure 1. Liquefaction damage distribution in Mihama-ku of Chiba City

There are a number of techniques that can be applicable to reduce the risk of liquefaction-induced damage during an earthquake. Dewatering is one of them, but this method is not suitable for the area where there exist no clayey stratum. A possible alternative is the method of partial saturation in which a fully saturated soil is converted into a partially saturated condition (Yegian et al. 2007; Eseller-Bayat et al. 2013). There is a possibility that this can be done by first lowering the groundwater level and then restoring it to the previous level.
This paper describes centrifuge shaking table tests conducted to examine the effectiveness of this de-watering and recovering process as a liquefaction countermeasure. The second part of this paper de-scribes a variety of in-situ measurements that have been conducted in the field where a demonstration experiment of dewatering was carried out, in order to verify this idea in an actual condition.

2 CENTRIFUGE MODEL TESTS

2.1 Test model

Figure 2 shows the test apparatus used. The scale of the model is 1/30, and the tests were performed under a centrifugal acceleration of 30 g. A laminar container was partitioned into two by an aluminum board and membrane, which prevent pore water flow from one side to the other but not to prevent shear deformation of a container. Both sides of the model ground were constructed equally and each consists of two layers: the base layer of coarse silica sand with the thickness of 50 mm and a surface layer of fine liquefiable sand with the thickness of 250 mm.

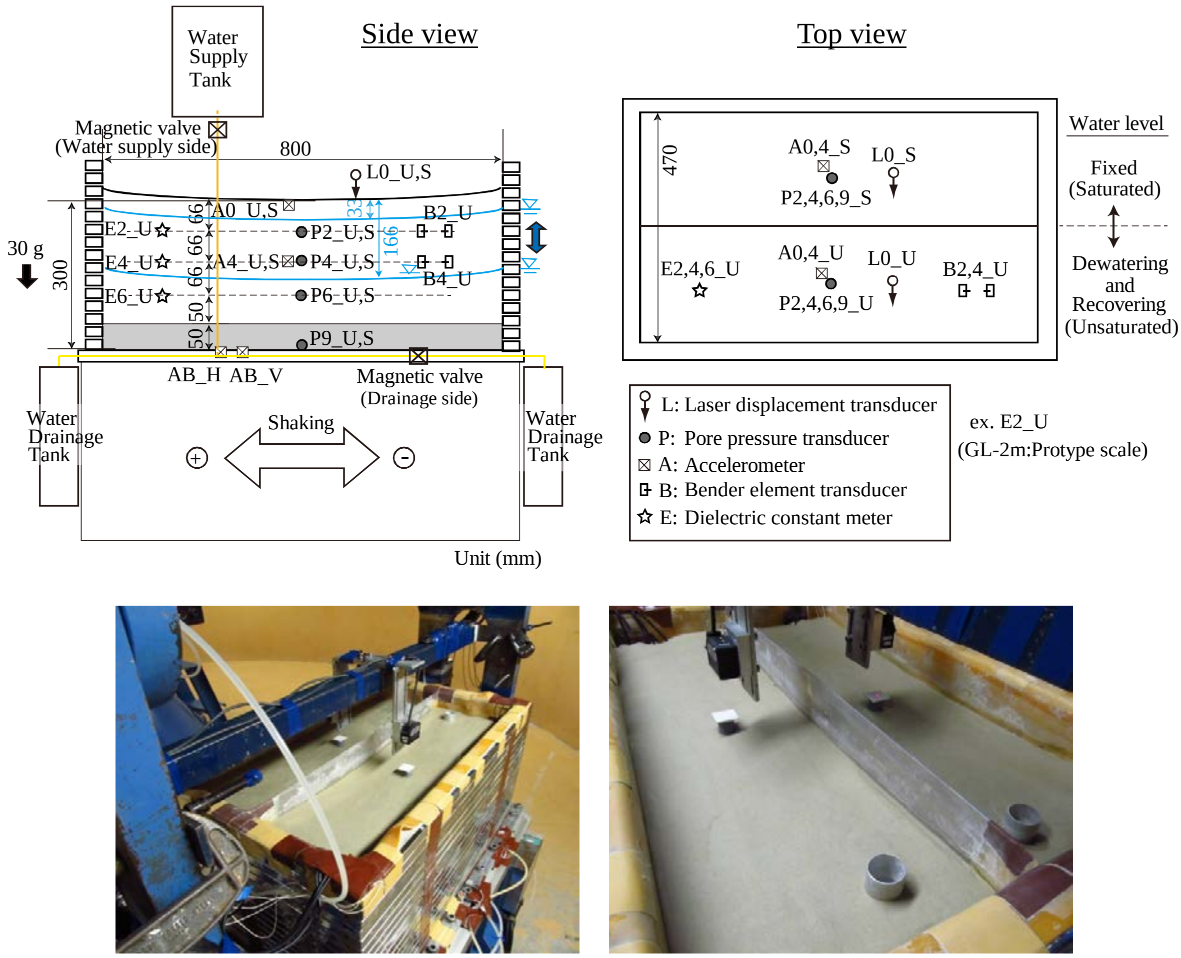


Figure 2. Outline of shaking table centrifuge model test

Four pore pressure transducers were placed at four levels in the ground of each side. Horizontal accel-erometers were placed on the container base plate, and at two locations in the ground. Laser displace-ment transducers were used to measure the settlement of the ground surface throughout the tests. Two pairs of bender elements to measure the P-wave velocity of the model ground and dielectric constant

meters to measure the degree of saturation (S_r) were set in the model ground of variable water level (dewatering and recovering) side.
Dry sand and clay were mixed to create a uniform soil in advance. The base layer was first constructed by tamping dry coarse sand. This coarse layer was used to level the pore fluid which was injected through the holes at the bottom of the container during saturation phase. On top of this layer, clayey sand was poured in and tamped so that the 25 mm thick layer has the designed density. This process was repeated 10 times until liquefiable layers became 250 mm thick. The model ground was deaired in a vacuum tank and was saturated with deaired water for one day. After confirming the saturation, the container was placed on the shaking table and the upper and lower water tanks were mounted on the arm and the shaking table.

2.2 **Physical properties of liquefiable layers**

Table 1 lists the physical property of clayey sand (Silica No.8 with 5 % Kaolin), which was used as liquefiable soils. For reference, physical property of clean Silica No.8 is also listed. The density of silica No.8 in clayey sand was controlled to have the same density of clean silica No.8 sand with D_r = 50 %. The permeability coefficient k of Silica No.8 with 5 % Kaolin clay was 3.3 × 10^{-6} m/s, which is almost 1/10 of that of clean Silica No.8 sand.
A series of centrifuge model tests have been conducted, but only the case with silica sand with Kaolin clay is described in this paper. Cases with clean silica sand without Kaolin clay gave similar results described in the following sections.
Figure 3 shows the grain size distribution curves.

Table.1 Physical properties of liquefiable soils

	ρ_s	e_{max}	e_{min}	k	D_{50}	ρ_d	D_r
	g/cm^3			m/s	mm	g/cm^3	%
Silica No.8 + Kaolin	2.636	1.377	0.757	3.3×10^{-6}	0.0779	1.392	78
Silica No.8 (Reference)	2.640	1.298	0.695	2.8×10^{-5}	0.0786	1.326	51

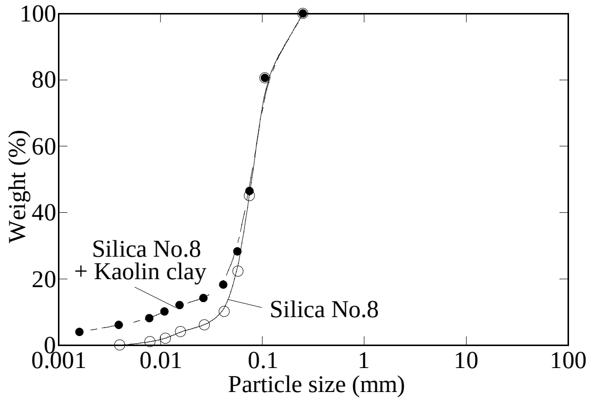


Figure 3. Grain size distribution curves for sand used in test

2.3 **Test procedures**

The adopted procedure is as follows:
1. Set the initial water level to 33 mm below the ground surface for both sides.
2. Increase the centrifugal acceleration to 30 g. Keep this acceleration until the end of the test.
3. Open the magnetic valve of water drainage side. Drawdown the water level by 133 mm (about 4 m in the prototype scale) at one side. Shut the valve and keep it about 3.4 h (about 101.6 h in the prototype scale)
4. Open the magnetic valve of water supply side. Recover the water level by 133 mm until initial water level is reached. Shut the valve and keep it about 3.3 h (about 98 h in the prototype scale).
5. Start shaking by applying the input motion (see Figure 5).

3 CENTRIFUGE TEST RESULTS

3.1 During water drawdown and recovery

Hereafter all values are given in the prototype scale.
Figure 4 shows the time histories of pore pressure *u* and saturation ratio S_r measured by dielectric constant meter. In the variable water side, *u* decreased by about 40 kPa or 4 m of total head and recovered to almost initial water level. On the other hand, S_r decreased by 30 to 50 % during dewatering and reached almost 90 % even after the water level was recovered to the initial level. Table 2 lists the P-wave velocity (V_p) change before, during and after dewatering and recovering water level. Initial value of V_p of 1250 ~ 1300 m/s decreased rapidly to 200 ~ 250 m/s due to dewatering and these values were maintained even after water level recovery. These results indicate that clayey sand layers keep unsaturated condition once it experiences the history of water level change. Thus, V_p may be used as an indicator to judge sand saturation or unsaturation, but it can not be used to measure S_r quantitatively.
One of the major concerns is how long this condition is maintained. It is reported that this unsaturated condition is maintained for at least three months according to a laboratory test (Ishikawa, et al. 2003, Shamoto 2005).

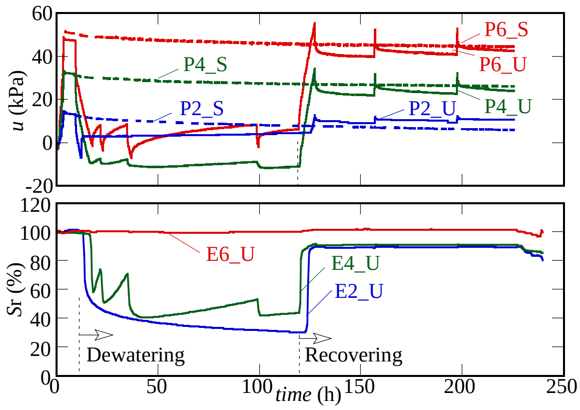


Figure 4. Time histories of pore pressures and S_r during dewatering and recovering water level

Table .2 measured V_p before, during and after dewatering and recovering water level

	V_p (m/s)		
	Before dewatering	During dewatering	After recovery
B2-U	1289	229	200
B4-U	1263	231	203

3.2 During shaking

Figure 5 shows acceleration time histories of the input wave and ground motions. Sinusoidal wave was used as the input. The maximum acceleration was approximately 2.2 m/s^2 (220 gal), the frequency was 2 Hz, and the number of cycles was 60 gradual increase, 20 steady state, 10 gradual decrease. Response accelerations of fixed water level side A0_S, A4_S decreased rapidly at 30s, 33s respectively due to liquefaction. In the variable water level side, response accelerations A0_U, A4_U also decreased after liquefaction.
Figure 6 shows that $\Delta u/\sigma'_v$. $\Delta u/\sigma'_v$ of fixed water level side P2_S, P4_S, P6_S reached 1.0 at 30 ~ 35s, which means the model ground of fixed water level side totally liquefied. While $\Delta u/\sigma'_v$ of variable water level side P2_U, P4_U did not reach 1.0, this means that this side of soil did not liquefy (P6_U liquefied because this pore pressure sensor is placed under the level of variable water).
Figure 7 shows time histories of surface settlement of the model ground. Settlement of fixed water level side was about 150 mm. While settlement of variable water level side was about 50 mm, almost one third of that of fixed water level side.
From these experimental results, it can be said that the ground which experiences the process of dewatering and recovering becomes unsaturated and their liquefaction resistance is improved.

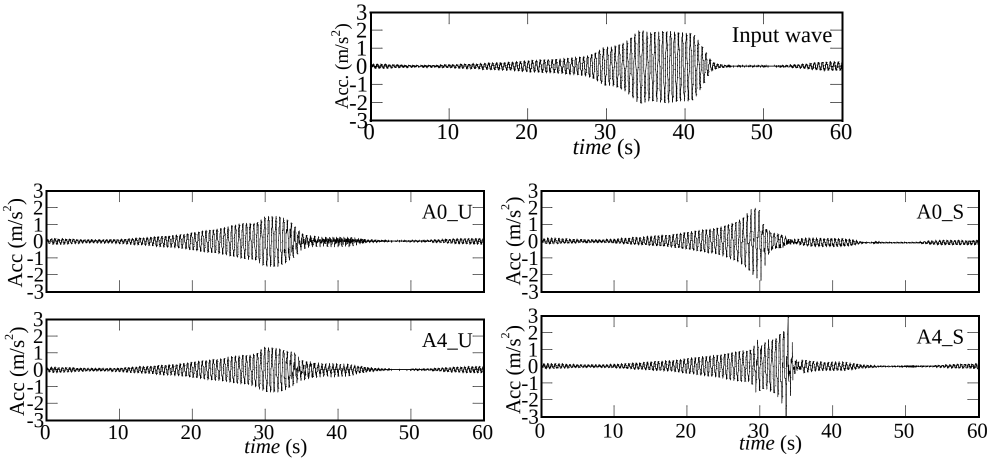


Figure 5. Acceleration time histories of input wave and ground motions

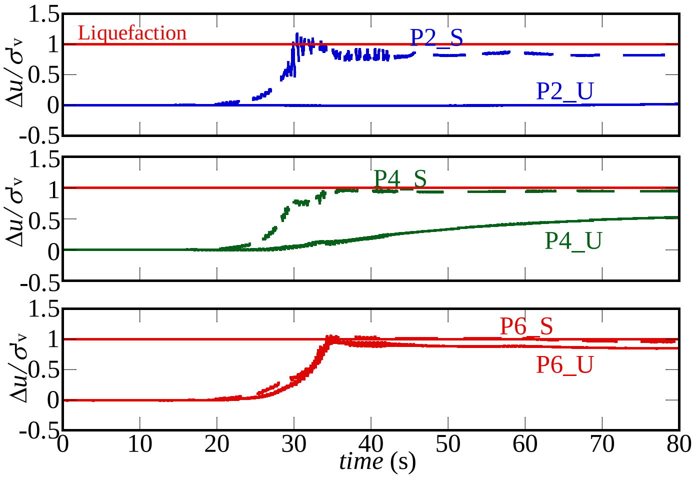


Figure 6. Time histories of excess pore water pressures

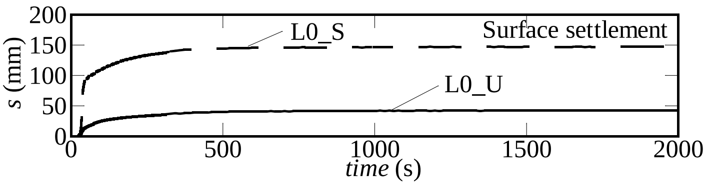


Figure 7. Time histories of surface settlement

4 IN-SITU MEASUREMENTS

4.1 Demonstration test

Chiba City has conducted a demonstration experiment of dewatering in a small park located in the target area where countermeasure is to be implemented. The target area is situated in one of the heavily affected areas shown in Figure 1. The authors have been involved in this experiment and conducted in parallel a variety of in-situ soil investigations before, during and after the experiment, including standard penetration tests, PS loggings, RI cone penetration tests, microtremor measurements and earthquake observations. Figure 8 shows a layout map of demonstration experiment along with the locations of soil investigations. As is illustrated in the figure, the experiment was conducted in such a way that the ground water was pumped up from two wells by collecting water through perforated pipes buried in the ground. The ground water level was lowered from about GL–1.0~1.5m (depending on the season and weather) down to GL–3m. The demonstration experiment started on October 13, 2013, and ended on September 30, 2014. Thus, the ground water level of GL–3m, which is lower by 2m from outside the sheet pile wall, had been kept for about a year.

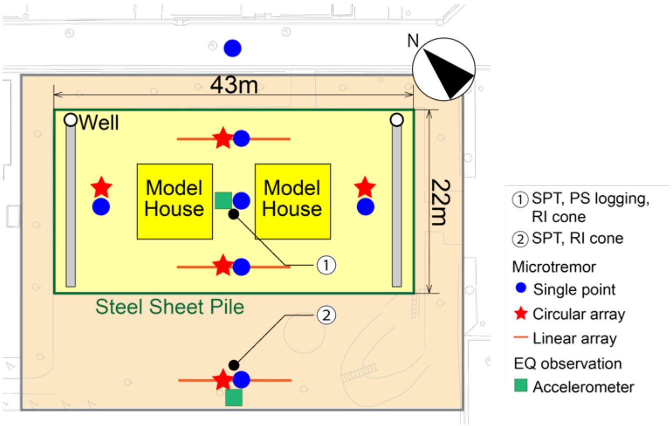
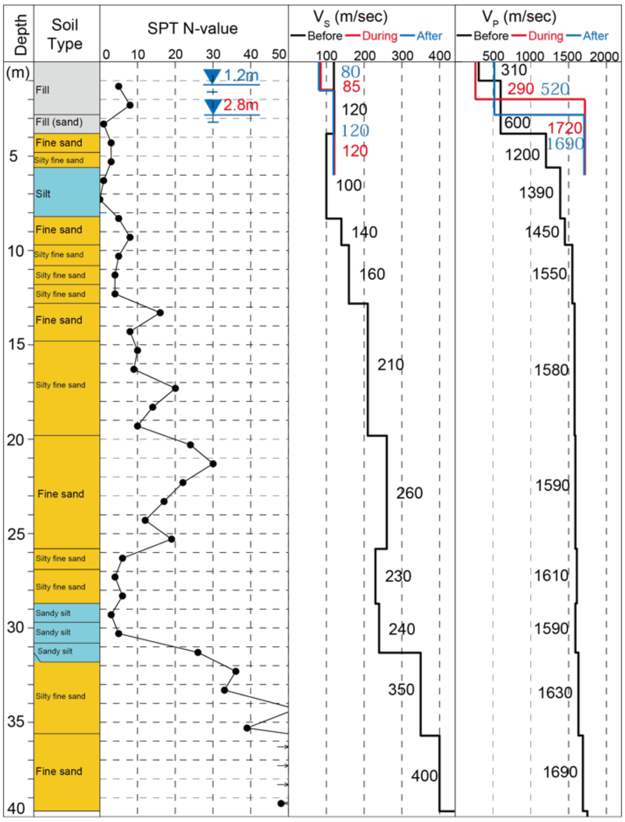


Figure 8 Demonstration experiment of dewatering

4.2 S and P wave velocity profiles



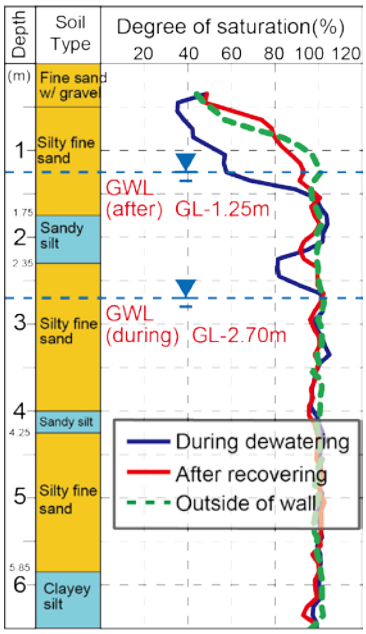


Figure 9(a). Boring and PS logs

Figure 9(b). Degree of saturation

Figure 9(a) shows the boring log with the SPT *N*-values along with the PS logs. The boring and PS logging were carried out before dewatering started. Another PS logging was performed during dewatering as well as after recovering. The test site is situated in the reclaimed land and the soil from the ground surface down to GL–8.2m is considered as fill. According to Figure 9(a), the shear wave velocity of the surface soil down to GL–4m was 120m/s before dewatering. During dewatering, the shear wave velocity decreased to 85m/s for the superficial layer down to GL–1.5m and increased to 120m/s for the underlying layer from GL–4m to GL–6m. More interestingly, the shear wave velocity does not seem to recover when restoring the ground water to the normal level (equal to the one outside the sheet pile wall). The P wave shows a similar trend in that the value decreased in the superficial soil and increased in the underlying soil. This indicates that the stiffness of the very shallow part of the soil decreased while that of the deeper part increased due to the process of dewatering and recovering. The increase of the stiffness of the deeper soil can be resulted from the increase of the effective overburden pressure due to dewatering.

4.3 **Degree of saturation**

Radio isotope (RI) cone penetration tests were carried out during the dewatering was in operation and after the ground water was restored, in order to examine the detailed soil layering and the degree of saturation of each layer. Figure 9(b) shows the resulting soil profile along with the distribution of the degree of saturation. In the figure, the degree of saturation during dewatering and after recovering, as well as the result measured at the location outside of the shield wall where the ground water was not lowered, are plotted. From this figure, it is noted that the surface soil consists of a number of thin layers when compared to Figure 9(a), in which a sandy silt located between the depth GL–1.75m and GL–2.35m was not identified. As for the degree of saturation of the surface soil, the silty sand located just above this sandy silt has higher saturation due probably to rainfall and the low permeability of underlying sandy silt. It is also noted that the silty sand located below GL–2.35m goes back to full saturation while the silty sand above GL–1.75 does not restore to full saturation with the degree of saturation of 91~98%, meaning that this part of soil (from GL–1.25m to GL–1.75m) remains unsaturated which suggests the increase of resistance against liquefaction.
An additional measurement of the degree of saturation is planned one year after the end of the demonstration experiment.

4.4 **Microtremor measurements**

The authors have conducted single point and array microtremor (ambient vibration) measurements in the experiment site before, during and after dewatering. Figure 10 shows the phase velocity dispersion curves. Although the peak period of H/V ratios of the single point measurement results does not change depending on the depth of the groundwater level, the phase velocity gives a larger value in the shorter period range by dewatering as well as recovering, which may correspond to the fact that the shear wave velocity of the deeper soil (of the surface layer) increased by lowering and recovering the ground water level. This observation result conforms to the one discussed in the previous section.

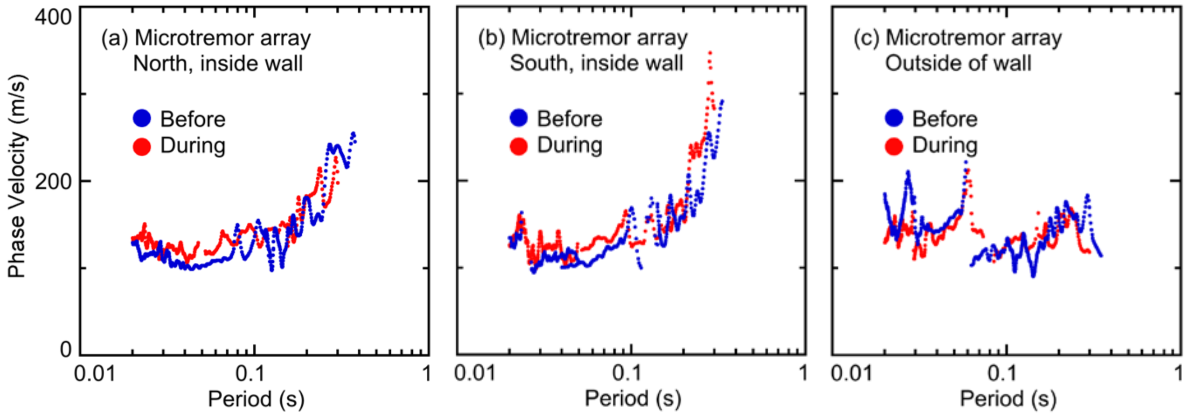


Figure 10. Phase velocity dispersion curves

4.5 **Earthquake observations**

In order to examine the effect of dewatering and recovering on the dynamic behavior of the ground, earthquake observations were performed during and after dewatering by installing accelerometers inside and outside the sheet pile wall. Figure 11 shows the Fourier spectral ratios of the recorded ground motions between inside (the ground water level is lowered) and outside (the ground water level is maintained) of the sheet pile wall. There is not much difference between inside and outside ground motions except for the very short period range. In fact, the Fourier spectral ratio between inside and outside locations indicate that amplifications are observed in the very short period range, as shown in Figure 11. It is also shown in the figure that amplification is observed also in the ratio between com-

puted transfer functions of inside and outside locations based on the soil profiles shown in Figure 9(a) by applying the one-dimensional wave propagation theory. This amplification can be resulted from the change of the soil profile from the stiffness point of view in that the stiffness was slightly decreased in the very shallow part while it was slightly increased in the deeper part and that it created an impedance gap between these two parts of the surface soil.
It is believed that this increase of soil stiffness in the deeper part can make the soil more resistive against liquefaction because the increase of stiffness decreases shear strain during an earthquake. Thus dewatering and recovering can improve liquefaction resistance of the soil by increasing the soil stiffness and decreasing the degree of saturation.

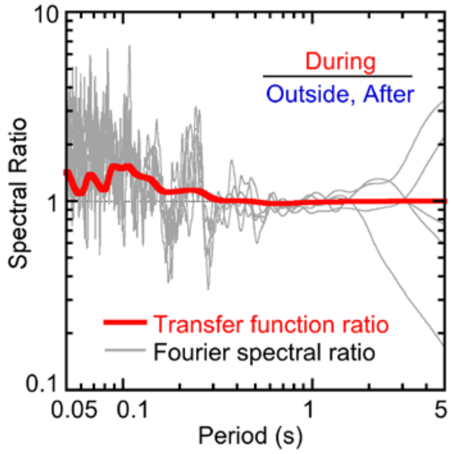


Figure 11. Fourier spectral ratios

5 CONCLUSIONS

In order to examine the effectiveness of the process of dewatering and recovering as a countermeasure against liquefaction during an earthquake, a series of centrifuge model tests have been conducted. In-situ measurements have also been conducted before, during and after a demonstration experiment of dewatering in an actual ground. It was found from these tests that:

(1) The dewatering and recovering process actually creates a layer of unsaturated soil.
(2) Due to the existence of this unsaturated soil, the thickness of liquefied soil layer is greatly decreased.
(3) It was confirmed that the same process can create a layer of unsaturated soil even in the actual ground.
(4) It was also confirmed that the stiffness of deeper soils can be increased due to this stress history.

REFERENCES:

Eseller-Bayat, E., Yegian, M. K., Alshawabkeh, A. & Gokyer, S. 2013. Liquefaction Response of Partially Saturated Sands. I: Experimental Results, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol 139 (6) 863-871.
Ishikawa, A., Kohsaka, N., Miyake, N. & Amari, N. 2003. Preventive measure of liquefaction by decreasing saturation ratio, *Proc. 38th Japan National Conference on Geotechnical Engineering*, 1977-1978. (in Japanese)
Sekiguchi, T. & Nakai, S. 2012. Liquefaction Damage Distribution in Mihama Ward of Chiba City during 2011 Tohoku Earthquake, *Proc. 15th World Conference on Earthquake Engineering*, Portugal, 2012, 10pp.
Shamoto, Y. 2005. Characteristics of saturated state of unsaturated sand specimen during permeability test, *Proc. 40th Japan National Conference on Geotechnical Engineering*, 1329-1330. (in Japanese)
Yegian, M. K., Eseller-Bayat, E., Alshawabkeh, A. & Ali, S. 2007. Induced-Partial Saturation for Liquefaction Mitigation: Experimental Investigation, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol 133 (4) 372-380.