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Shaking table experimental study for liquefaction countermeasures on adjusting unsaturated ground by changing ground water level

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ABSTRACT: The purpose of this study is to confirm liquefaction countermeasures utilizing the fact that the degree of saturation does not return completely and the unsaturated state, which is achieved by lowering the ground water level, maintains even after raising the ground water level again. Shaking table tests with model ground of saturated state and model ground of unsaturated state which is achieved by lowering and recovering the ground water level were carried out. Experimental results show that unsaturated state was suppressed by increasing the pore water pressure and maintaining the excess pore pressure ratio to be less than 1, as well as the effectiveness of the liquefaction countermeasure was confirmed. Furthermore, although the degree of saturation increased after the shaking, it did not completely recover to the state before the water level was lowered. Therefore, it was suggested that the unsaturated state is persistent after shaking.

1 INTRODUCTION

In the case where the liquefied layer is located at the position where cut and cover tunnels are to be constructed, liquefaction countermeasures may be taken by a chemical injection method or the like to make sure floating does not occur during earthquake. However, the total construction costs will increase by implementing this method.

Therefore, as shown in Figure 1, instead of adjusting the liquefaction layer by injecting a chemical liquid or the like, we are studying a liquefaction countermeasure method that adjust the surrounding ground to be unsaturated by lowering the ground water level using deep well construction method (Pumping up groundwater) etc., thus the bottom plate is stabilized during construction period. It is unnecessary to separately prepare liquefaction countermeasures by this method, so that the total construction costs can be reduced.

Sawada et al. (2016) confirmed that once the unsaturated state is adjusted by lowering and recovering of the groundwater in the model ground, it will not be fully saturated even afterwards, and the unsaturated state will maintain. In addition, Sakamoto et al. (2018) has confirmed that the same experiment results were shown in a small scale soil tank and a cylindrical soil tank with a large depth.

However, is was unclear about the effectiveness of liquefaction countermeasures after earthquake, and whether the unsaturated state will sustained even after the earthquake.

Therefore, in this paper, a model ground was made and unsaturated ground was adjusted by lowering and recovering the groundwater. Shaking table experiments were done to confirm the effect of liquefaction countermeasure and the sustainability of unsaturated state after shaking.

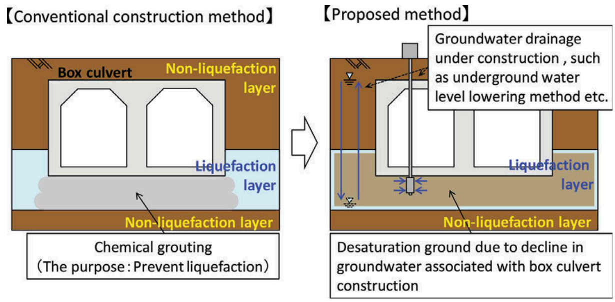


Figure 1. Image of liquefaction countermeasures on adjusting unsaturated ground

2 EXPERIMENT OUTLINE

Since the phenomenon of unsaturation is similar between a ground with a large depth and a ground in a small scale, shaking table tests were carried out in a small scale model of ground. Table 1 shows experimental conditions and Table 2 shows physical properties of ground materials used in the model. Two cases were simulated in experiments, the saturated ground for Case 1 and the ground unsaturated by lowering and raising the water level for Case 2.

The soil material used in tests were Silica sand No. 6, and model grounds were made with a relative density of 60% by water pluviation. The relative density of 1.5m/s^2 shaking table test is the average calculated by converting from the amount of settlement after the 1.0m/s^2 shaking table test just performed. Degassed water were used to make the saturated ground.

Figure 2 shows the outline of the model ground and the arrangement of measuring instruments. The soil tank used in the experiment is a laminar shear tank with a width of 1.5 m, a length of 0.4 m, and a height of 0.7 m (inner dimension).

The measuring instruments were installed with 7 pore water pressure gauges, 7 accelerometers to measure response acceleration, 3 soil moisture sensors to measure the volume water content (VWC) by measuring the dielectric constant, and 1 laser displacement meter. Excess pore water pressure, horizontal acceleration, degree of saturation and the amount of settlement of the model ground were measured.

Figure 3 shows the input acceleration waveforms. Two types were used for the input waves: one is 20 waves of 3 Hz sine wave with 1.0m/s^2 as maximum acceleration and another one is 20 waves of 3 Hz sine wave with 1.5m/s^2 as maximum acceleration.

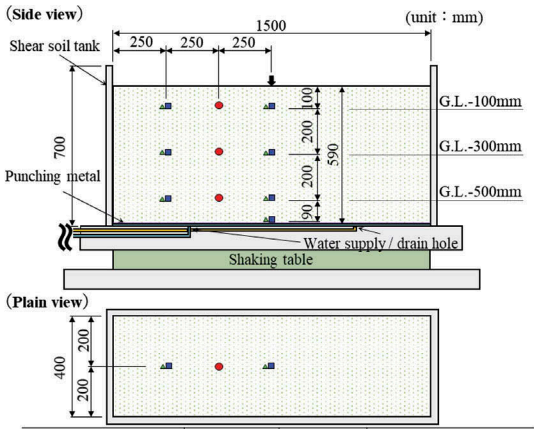
Firstly, the soil tanks were shaken by maximum acceleration of 1.0m/s^2 as an input wave, and the pore water pressure etc. of each layer were measured and confirmed. After that, sand was added to the ground surface settled by 1.0m/s^2 shaking, equivalent to the relative density

Table 1. Experimental conditions

Case	Countermeasure method	Ground material	Ground creation method	Input wave		Relative density
case1	—	Silica sand No.6	Water pluviation (using degassed water)	3Hz× 20 wave ×	1.0m/s^2	60%
					1.5m/s^2	75%
case2	Pumping / Rechage method				1.0m/s^2	60%
					1.5m/s^2	73%

Table 2. Value of Silica sand No.6

Density of soil particles ρs	g/cm^3	2.643
Maximum density	g/cm^3	1.694
Minimum density	g/cm^3	1.389
Fine fraction content Fc	%	0.3
Uniformity coefficient Uc	—	2.2
Coefficient of curvature Uc'	—	1.37



Type of sensor	Model number	Manufacturer	Range
▲ pore water pressure gauge	P310A-03	SSK	max. 0.3kgf/cm²
■ accelerometer	A5-1	SSK	±1G
● soil moisture sensor	5TE	METER	0～1 m³/m³(0～100%VWC)
⬇ laser displacement meter	LB-01	Keyence	±40 mm

Figure 2. Outline of experiment equipment

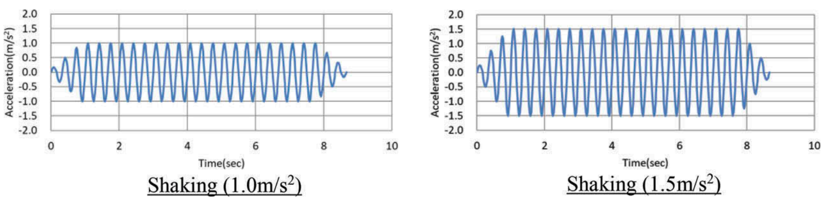


Figure 3. Input acceleration

of model ground after shaking. After confirming that the excess pore water pressure increased due to the shaking of 1.0m/s^2 disappeared, the soil tanks were shaken with the maximum acceleration of 1.5m/s^2.

3 ADJUSTING UNSATURATION GROUND BY CHANGING GROUND WATER LEVEL

After settling the model ground described in Chapter 2, unsaturation goal was achieved for ground soil by lowering and raising water level in Case 2.

3.1 *Method of lowering and raising the water level*

Figure 4 shows the method of lowering and raising the water level. An external tank was connected to the bottom of the soil tank with a hole to supply and drain water, thus by adjusting the water level of the connected external tank, the lowering and raising of the water level would be achieved in the soil tank.

Figure 5 shows the changes of water level in the soil box over time. After lowering the water in the external tank to G. L. -500 mm about 1.5 days, the water level was maintained for about 8 days and raised again for about 1.5 days. In addition, tap water was used for recharging, considering the fact that the groundwater contains air in the practical ground.

3.2 *The degree of Saturation changes due to lowering and raising of water level*

Figure 6 shows changes of the degree of saturation in the model ground by lowering and raising the water level over time before shaking. In Figure 6, the time required for pumping and

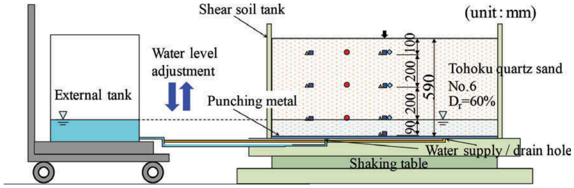


Figure 4. Image of adjusting the water level in the soil tank

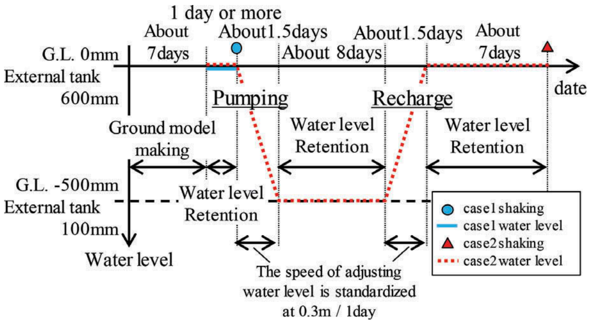


Figure 5. Changes of water level in the soil tank over time

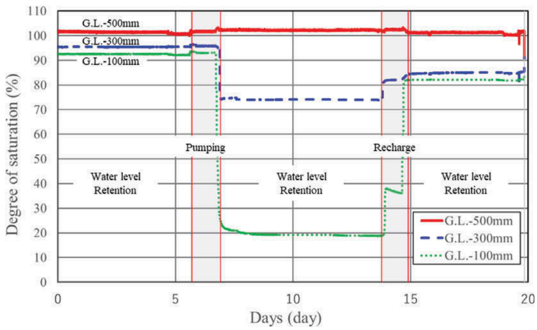


Figure 6. Change of degree of saturation (case2)

recharging the water in the external tank is indicated by gray shading. The degree of saturation was calculated from the volume moisture content measured by the soil moisture sensor.

Due to the pumping of the water in the external tank, the degree of saturation at G. L. -100 mm decreased to about 20%, whereas the degree of saturation at G. L. -300 mm decreased to about 75%. After the recharging of the water in the external tank, the degree of saturation at G. L. -100 mm and G. L. -300 mm was about 80% to 85%, and no significant differences were found among them. In addition, we confirmed that the degree of saturation did not decrease simultaneously with the level of the external tank but tended to decrease at the timing later than the external tank water level.

Specifically, the degree of saturation at G. L. -100 mm decreased when the water level of the external tank was lowered to 300 mm (equivalent to G. L. -300 mm), and similarly, the degree of saturation at G. L. -300 mm decreased when the water level of the external tank was lowered to 100 mm (G. L. -500 mm). As a result, there was a 200 mm-difference between the water level of the external tank and the water level when the degree of saturation decreased.

The degree of saturation at G. L. - 500 mm, which is the lowest depth of the water level, remained around 100%, and no fluctuation according to pumping and recharging was observed.

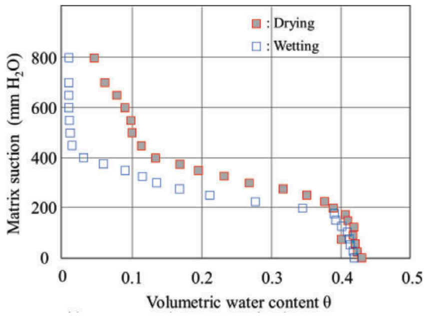


Figure 7. Soil water characteristic curve

By lowering and restoring the water level in the soil tank, the saturation at G. L. -100 mm and G. L. -300 mm did not become saturated again, and an unsaturated zone was achieved.

Also, we thought the reason for the difference between the decrease in the degree of saturation at G. L. -100 mm and that at G. L. -300 mm after pumping and the 200 mm- difference when lowering of water level, was due to moisture retention characteristics of Silica sand No. 6 used as soil material. According to Kobayashi (2012) et al., Silica sand No. 6 showed to hold moisture up to ground water level + 200 mm (Figure 7). This is consistent with the result of this time when the degree of saturation decreased after lowering the water level by about 200 mm from the measurement position of the degree of saturation.

4 SHAKING TABLE TEST

4.1 *Measurement data at shaking*

Figure 8 shows the excess pore water pressure ratio changes over time, Figure 9 shows horizontal acceleration at 1.0m/s^2 shaking over time and Figure 10 shows the ground surface vertical displacement at 1.0m/s^2 shaking. The excess pore water pressure ratio is calculated by the excess pore water pressure from the measurement value of the pore pressure gauge at each measurement place over time of each case. Note that the effective upper pressure at the time of calculating the excess pore water pressure ratio is calculated assuming that the degree of saturation is 100%.

The data of 1.5m/s^2 shaking is posted as reference data because the relative density has changed due to the 1.0m/s^2 shaking performed immediately before.

4.1.1 *Measurement result*

In Case 1, from Figure 8, the excess pore water pressure ratio exceeds 1.0 and it reaches liquefaction almost over the entire range immediately after the shaking. As shown in Figure 9, with the occurrence of liquefaction, the horizontal acceleration amplitude at G. L. -100 mm is decreasing. Figure 10 shows that the amount of settlement of ground surface was 13 mm.

In Case 2, from Figure 8, it can be confirmed that the excess pore water pressure ratio is lower than 1.0 in the whole region and does not reach liquefaction. In particular, the effect of suppressing the rise in excess pore water pressure is remarkable at the positions of G. L. -100 mm and G. L. -300 mm where the unsaturated region is formed. However, comparing G. L. -100 mm with G. L. -300 mm, the excess pore water pressure ratio was smaller in G. L. -100 mm, and even in the same unsaturated zone, the effect of suppressing the rise in excess pore water pressure was different. In addition, as shown in Figure 6, the effect of suppressing the rise in excess pore water pressure was confirmed even at the position of G. L. -500 mm, which is considered as saturated state comparing with Case 1.

Figure 9 shows that the horizontal acceleration amplitude at G. L. -100 mm is not lower than in case 1. Figure 10 shows that the ground surface settled about 3 mm immediately after the shaking, and the final settlement amount was 6 mm.

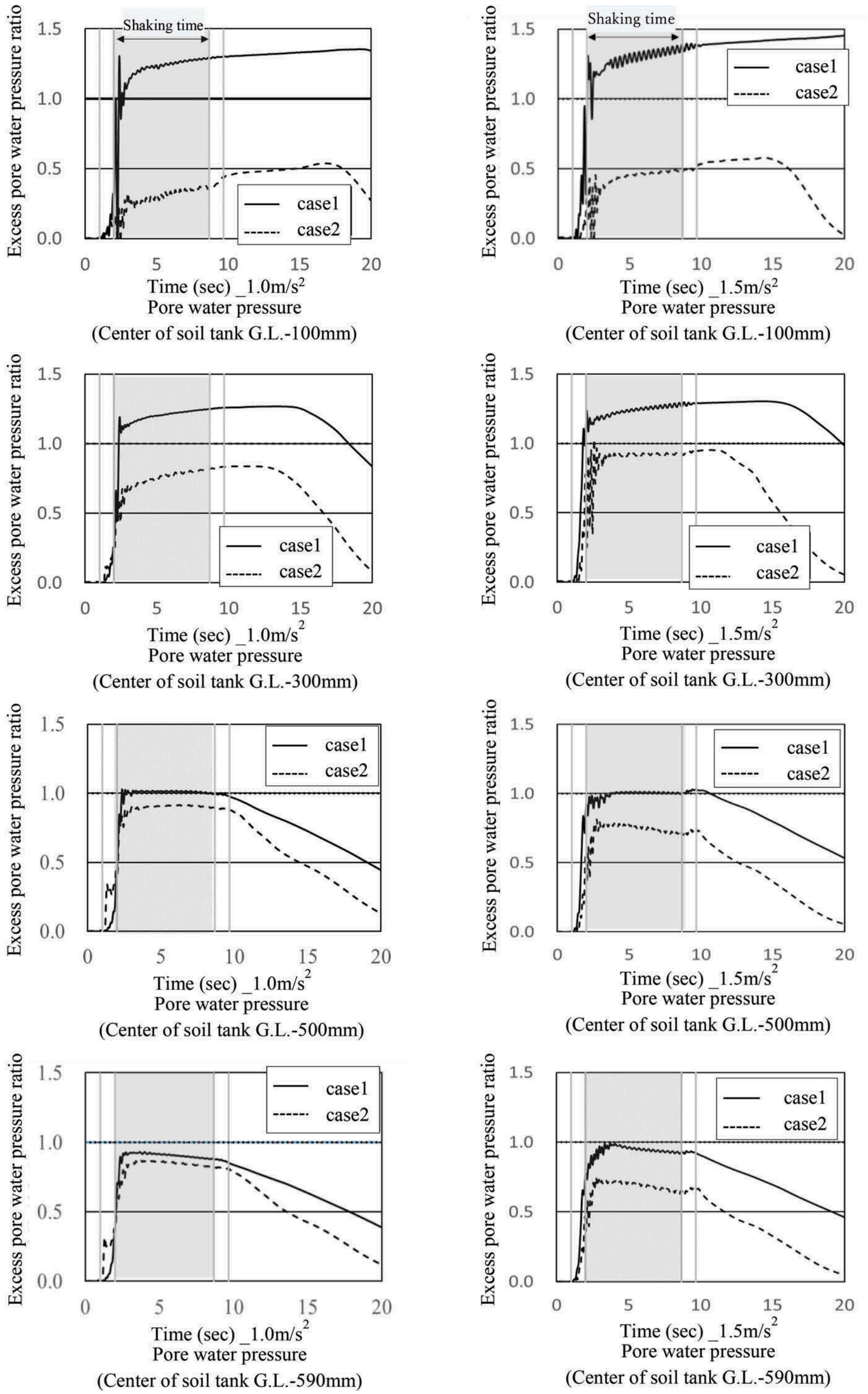


Figure 8. Measurement data over time series

4.1.2 *Discussion*

The degree of saturation at G. L. -100 mm, G. L. -300 mm, where the unsaturated zone was made, was about 80% to 85%, which was not a big difference, however the effect of

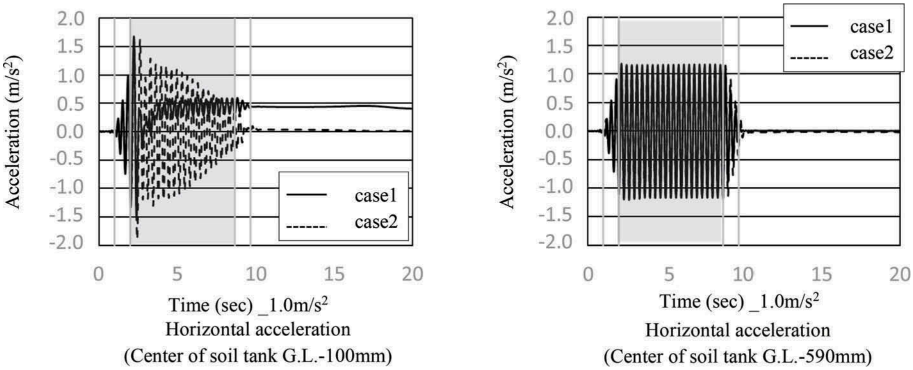


Figure 9. Horizontal acceleration

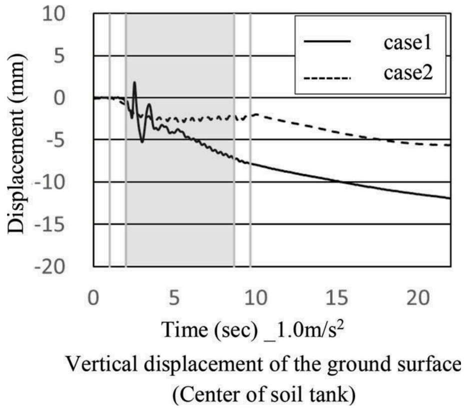


Figure 10. Settlement of the ground surface

suppressing the pore water pressure increase showed a significant difference comparably. This is because the pore water pressure at G. L. -300 mm is affected by the rise of the water pressure in the lower layer.

The effect of suppressing the rise in the pore water pressure was also confirmed in G. L. -500 mm as saturated state, which is due to the water pressure suppression effect of the unsaturated zone above G. L. -500 mm.

As a result, the effect of suppressing the rise in the pore water pressure was confirmed among all the zones where the water was lowed and raised. In addition, the effects were different at each depth, and it was confirmed that the shallower the layer is, the higher the countermeasure effect shows.

4.2 *Changes in the degree of saturation after shaking*

Figure 11 shows the changes of the degree of saturation over time before and after shaking in Case- 2. Figure 11 shows the degree of saturation at $1.0m/s^2$ shaking and $1.5m/s^2$ shaking and the degree of saturation before the water level is lowered (before pumping) at each measurement position.

The degree of saturation was calculated from the volume water content measured by the soil moisture sensors by the Topp‘s equation (Topp et al., 1980). The degree of saturation at G. L. -100 mm was 82% before $1.0m/s^2$ shaking, but it increased to 84% after shaking. Similarly, the degree of saturation at G. L. -300 mm increased from 85% before $1.0m/s^2$ shaking to 92% after shaking.

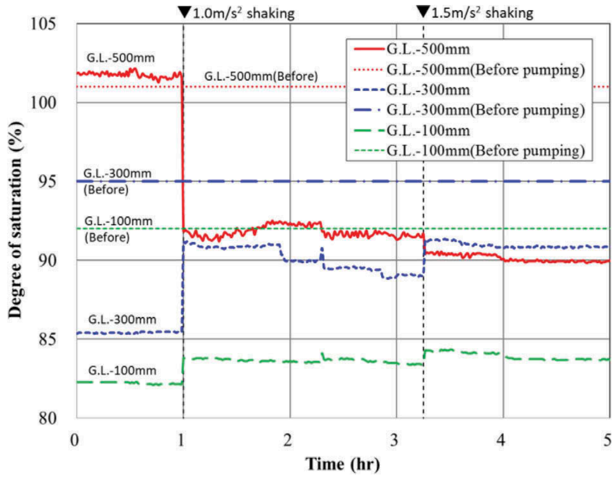


Figure 11. Change of the degree of saturation (Before and after shaking)

However, in any case, the degree of saturation did not rise to the original degree before the water level was lowered. On the other hand, the degree of saturation at G. L. -500 mm, which was 102% before 1.0m/s^2 shaking, has decreased to 93% after shaking. Although there was a difference in the amount of increase and decrease, the same tendency, which was confirmed before and after 1.0m/s^2 shaking, showed before and after 1.5m/s^2 shaking as well.

The reason why the degree of saturation at G. L. -100 mm and G. L. -300 mm were increased after shaking, is that the pore water pressure increased due to the shaking and the pore water moved upward from the saturated zone at G. L. -500 mm.

Although the degree of saturation of the unsaturated zone was increased after shaking, it did not rise to the degree of saturation before the water level was lowered, and it is considered that the unsaturated state may sustain even after shaking.

5 CONCLUSION

In this paper, shaking table tests were carried out on a liquefaction countermeasure utilizing adjusting unsaturated zone by lowering and raising ground water level, and the effect of countermeasures and the sustainability of the decrease of degree of saturation after shaking was confirmed.

The following conclusions can be drawn.

1. The effect of liquefaction suppression was confirmed due to suppressing the rise in the pore water pressure according to the model ground where the unsaturated zone adjusted by lowering and raising the ground water level. The liquefaction inhibiting effect varies from depth to depth, and it was confirmed that the shallower the layer is, the more significant effect shows.
2. The degree of saturation increased in the unsaturated area after shaking, however it did not completely recover to the degree of saturation before the water level was lowered. Therefore, there is a possibility that the unsaturated state (countermeasure to liquefaction) will sustain after shaking.

The shaking table test on the model ground confirmed the effect of the liquefaction countermeasure utilizing adjusting unsaturated ground by lowering and raising the ground water level, and the sustainability of the liquefaction countermeasure effect after the shaking was confirmed. We will continue studying the range of unsaturated zone, long-term sustainability of actual unsaturation in the ground and constructing a design method towards practical scale grounds.

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