Research on liquefaction prevention methods for detached houses using glass granulated sand and sheet pile closing method

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ABSTRACT

In recent years, liquefaction damage has been widely reported in Japan due to occurrences of large-scale earthquakes. Even in Kochi Prefecture, it is an urgent task to implement liquefaction countermeasures in detached houses and coastal areas in preparation for the Nankai Trough Giant Earthquake. In this study, regarding the liquefaction countermeasures for detached houses, the effect of liquefaction countermeasures when the ground of the residential land was replaced with Glass granulated sand was examined. Furthermore, the effectiveness of the Sheet pile closing method as a countermeasure against liquefaction was also investigated. This study was carried out using our university's dynamic Centrifuge. In a study of Glass granulated sand, it was confirmed that replacing the surface layer with Glass gravel with a relative density of 50% or more was sufficient to prevent liquefaction. In addition, the Sheet pile closing method was confirmed to be effective against liquefaction by embedded in the ground with a relative density of 70% or more.

Key words: *Liquefaction, Glass granulated sand, Sheet pile closing method, Centrifugal model test*

1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake, liquefaction occurred in a wide range from the Tohoku region to the Kanto region, and concentrated in the reclaimed land in Tokyo and Chiba Prefecture and the Tone River basin. Most of the damage due to liquefaction was on the foundations of detached houses, and some reinforced concrete low-rise buildings were also damaged (Ministry of Land, Infrastructure, Transport and Tourism. (2011)).

In Japan, the Nankai Trough Giant Earthquake is expected to occur in the not too distant future. Kochi Prefecture is surrounded by steep mountains, so it may not be possible to receive immediate rescue and assistance on land when the disaster happens. Therefore, in Kochi Prefecture, it is necessary to take measures against liquefaction in detached houses and coastal area (Kochi Prefecture (2013)).

In this study, we will examine the effect of liquefaction countermeasures using Glass granulated sand. Glass granulated sand is a recycled material made by granulating Glass into dice shapes using a special crushing method to eliminate sharp edges and make it safe to use.

The material characteristics of Glass granulated sand are that they have a lower density than sand, high water permeability, a wide range of optimum water content, and high liquefaction strength. In addition, it has a small swellimg ratio, so if it is applied to the foundations of detached house sites, it will also prevent reliquefaction.

In addition, regarding the Sheet pile closing method, we will examine the effect of preventing liquefaction by suppressing pore water pressure due to blocking of shear waves when the foundation ground of a residential property is closed in a rectangular manner.

As the research method, the dynamic Centrifuge was used. The effectiveness of the proposed method against liquefaction will be examined.

2. Features of Glass granulated sand

Currently, about 1.07 million tons of Glass bottles are supplied to the market as products every year in Japan. As a Glass bottle recycling system, there are cases where a Glass bottle is used repeatedly and cases where it is crushed and reused as a raw material for a new Glass bottle. However, 380,000 tons of Glass bottles are discarded annually in landfills. Glass Sourcing Co., Ltd. has established a recycled Glass granulation system with a processing capacity of 50 tons per hour. Glass granulated sand is recycled Materials in which Glass bottles are granulated into dice by a special method to eliminate sharp corners (Glass Resourcing Co., Ltd. (2019)). Glass granulated sand is characterized by high permeability and low swelling ratio than mountain sand. Therefore, Glass granulated sand is a material that can be expected to suppress not only liquefaction but also re-liquefaction.

Glass granulated gravel is a material in which only the gravel (2 mm sieve residual portion) is extracted in order to further increase the liquefaction countermeasure effect. Hereinafter, we will distinguish between these and call them Glass sandy-gravel and Glass gravel. **Fig. 1** shows Glass sandy-gravel and Glass gravel.

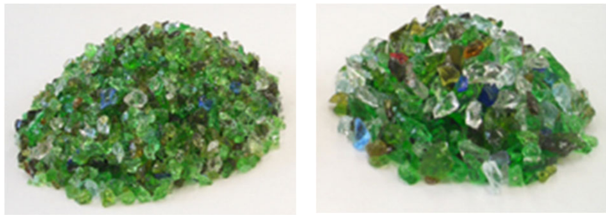

Fig. 1 Glass sandy-gravel and Glass gravel

Fig. 2 shows the particle size accumulation curve. Glass granulated sand (Glass sandy-gravel) has a particle size of 0.075 to 5 mm. Glass gravel is a material that has been passed through a 2mm sieve to further enhance its effectiveness as a countermeasure against liquefaction. Toyoura sand is a material that easily liquefies, consisting of fine sand with a uniformity coefficient Uc = 1.91 and an average grain size D_{50} = 0.19 mm, and is used as a liquefaction layer in Centrifugal force model experiments.

The red line is Japan's reference line, which indicates that particles smaller than this line have the potential for liquefaction and require a determination of liquefaction (Japan Road Association (2012)).

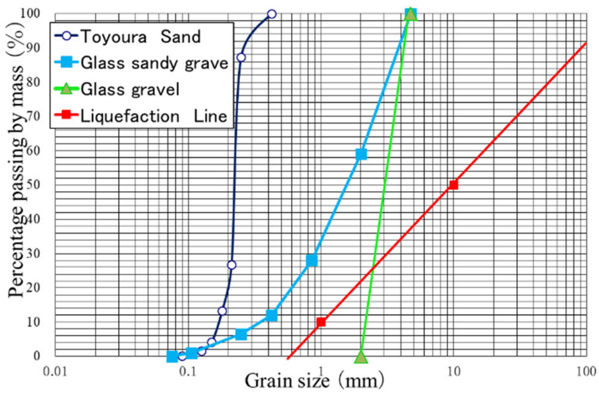

Fig. 2 Grain size distribution of Glass granulated sand

Table 1 shows the physical properties of Glass granulated sand, Glass gravel, and Toyoura sand. Maximum and minimum density tests and permeability tests were performed in our geotechnical engineering laboratory. Since Glass gravel has a large particle size of 2 to 5 mm, the maximum density and minimum density tests were conducted using a compaction test mold with a diameter of 10 cm and a height of 12.6 cm. The permeability test was conducted using a constant head permeability test.

Table 1. Physical properties of Glass granulated sand

Item	Unit	Glass sandy-gravel	Glass gravel	Toyoura sand
Density ρ_s	g/cm³	2.501	2.501	2.64
Maximum Density ρ_{tmax}	g/cm³	1.775	1.550	1.641
Minimum Density ρ_{tmin}	g/cm³	1.376	1.300	1.338
Coefficient of permeability (Dr=50%)	m/s	2.19×10^{-3}	1.14×10^{-2}	1.00×10^{-3}
Coefficient of permeability (Dr=70%)	m/s	1.12×10^{-3}	1.87×10^{-2}	3.00×10^{-3}
Swelling ratio	%	0.0013	—	—

The liquefaction strength test for the Glass sandy-gravel and the Glass gravel were conducted by the cyclic box shear tester at Kochi National College of Technology.

Fig. 3 shows the liquefaction strength test results of Glass sandy-gravel and Glass gravel at Dr=50% and Dr=70%. From **Fig. 3**, the results of Dr=50% for Glass sandy gravel and Glass gravel are almost similar, Dr=70% for Glass sandy-gravel is slightly larger, and Dr=70% for Glass gravel is extremely large.

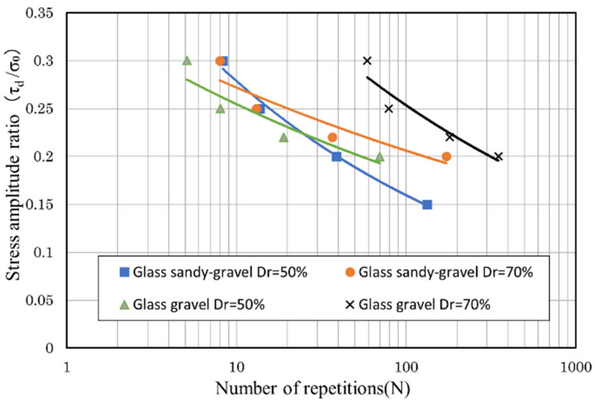

Fig. 3 Liquefaction resistance of Glass granulated sand

3. Experimental method

3.1 Experiment model

This study was conducted at a centrifugal acceleration of 40G. The shaking table acceleration of this device in a 40G field is about 6000 gal, and in the actual field it is 150 gal, which is 1/40th. Based on the simplified judgment method in the Highway Bridge Specifications (2017), the shaking table acceleration required to cause liquefaction in the experimental soil layer was calculated to be approximately 120 gal. For this reason, we conducted experiments in a 40G field.

Fig. 4 shows the input seismic waves of the shaking table in an actual field. The maximum acceleration is approximately 150 gal.

Fig. 5 shows a diagram of the ground model of a detached house. Pore water pressure gauges (p1 to p6) were installed in the ground to measure excess pore water pressure. In addition, the amount of settlement of the detached house was measured using a laser displacement meter, and the slope of the detached house was determined from the position of the bottom of the detached house before and after the experiment.

Fig.6 shows an example of a photograph (Case6) of an experiment the Glass gravel.

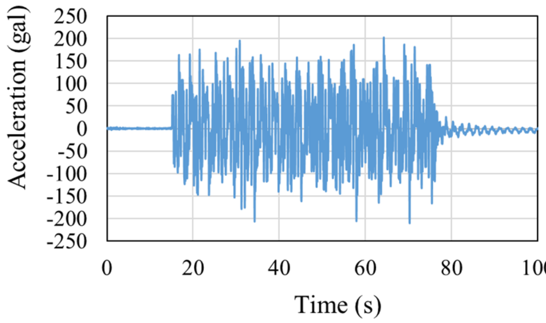

Fig. 4 Input seismic waves of the shaking table

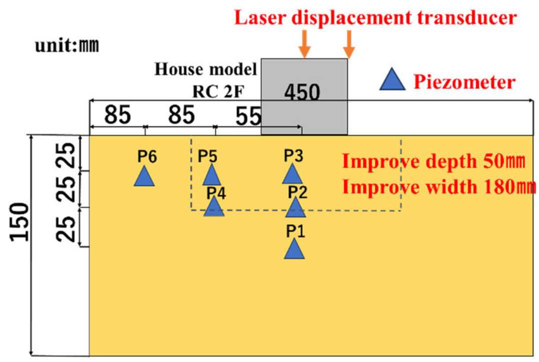

Fig. 5 Experimental model for the Detached house

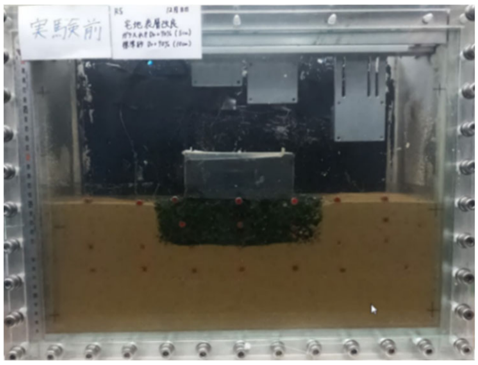

Fig. 6 Photograph of an experiment for Glass gravel

Fig.7 shows an example of a photograph of the Sheet pile closing method (Case 8). **Fig.8** shows the well part below the detached house. The dimensions of the well are 120 x 130 mm, the same as the foundation of the residential land.

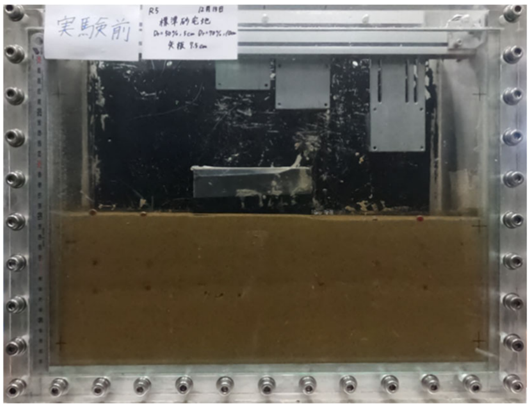

Fig.7 Photograph of the Sheet pile closing method

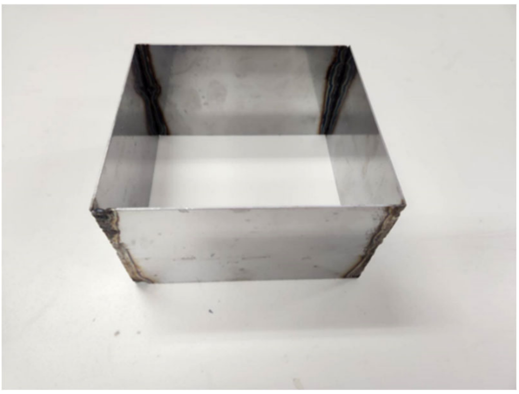

Fig. 8 Photograph of well part under the detached house

The model sheet pile was made of stainless steel metal (material: SUS430, Young's modulus: 200×10^3 N/mm^2, moment of inertia: 1.71×10^{-8} mm^2, thickness: 1.0mm). The well part showed no deformation at all after the experiment, and it is considered to have sufficient rigidity.

3.2 Experimental Cases

Table 2 shows the experimental cases. The ground model includes Toyoura sand (G_s=2.640, e_{max}=0.973, e_{min}=0.609, k=1.00×10^{-4} m/s) and Glass gravel (G_s=2.501, e_{max}=0.924, e_{min}=0.614, k=1.87×10^{-2}m/s), the 50% relative density layer was compacted by the underwater drop method, and the 70% layer was compacted by the air drop method.

Table 2. Experimental cases

	Conditions	Surface /base layer	Relative density
Case	Sample name /pile length	H（mm）	Dr(%）
Case1	Toyoura Sand	150	50
Case2	(untreated)		70
Case3	Toyoura Sand	50	50
	(untreated)	100	70
Case4	Galass gravel	50	50
	Toyoura Sand	100	50
Case5	Galass gravel	50	50
	Toyoura Sand	100	70
Case6	Galass gravel	50	70
	Toyoura Sand	100	70
Case7	Toyoura Sand (Sheet pile 750mm)	150	50
Case8	Toyoura Sand	50	50
	(Sheet pile 750mm)	100	70

The model container is 450mm width, 139.8mm depth, and 150mm height. The mass of the house model was 1.248 kg, and an RC structure with a width of 120 mm, depth of 130 mm, and height of 50 mm was used. In all cases, the width of the surface layer improvement was 180 mm and the depth of improvement was 50 mm. In addition, the allowable settlement for the detached house was set at 80 mm in actual size, and the allowable value was set at less than 10/1000 for slopes due to differential settlement, taking into account health aspects and damage to the house. (Architectural Institute of Japan (2008), Japan Geotechnical Society (2012))

Fig.9 to **Fig.11** show Cases 1 to 3 of the untreated ground experiment. **Fig.12** to **Fig.14** show Cases 4 to 6 of the liquefaction countermeasure experiment on the detached house using Glass gravel, and **Fig. 15** and **Fig.16** show Cases 7 and 8 of the liquefaction countermeasure experiment using the Sheet pile closing method.

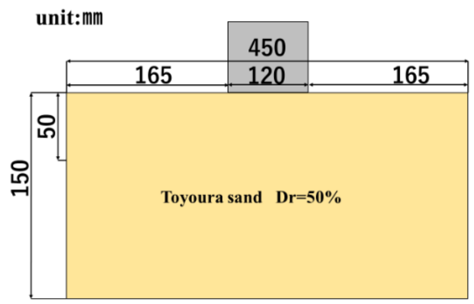

Fig. 9 Case1 ; untreated

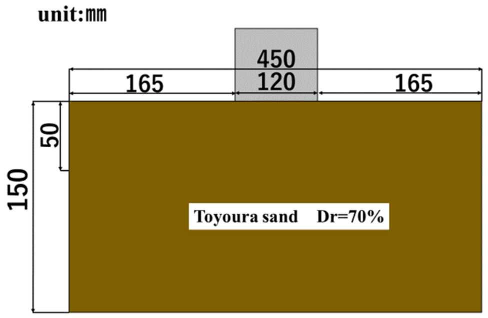

Fig. 10 Case2 ; untreated

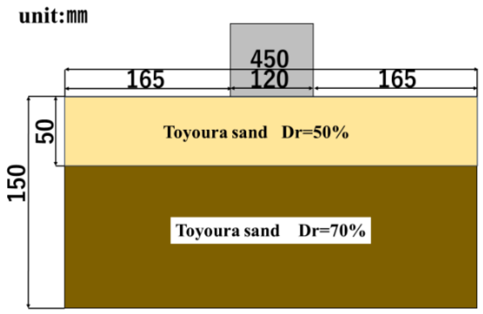

Fig.11 Case3 ; untreated

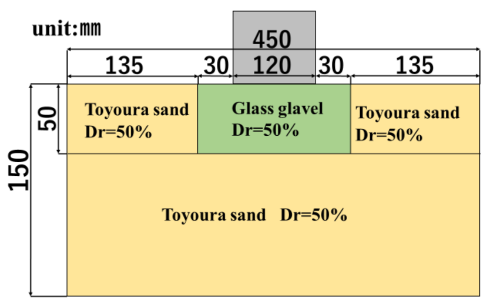

Fig.12 Case4 ; Glass gravel Dr=50%

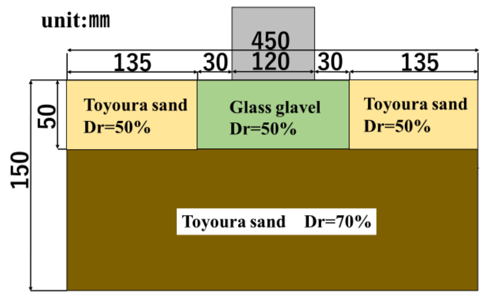

Fig.13 Case5 ; Glass gravel Dr=50%

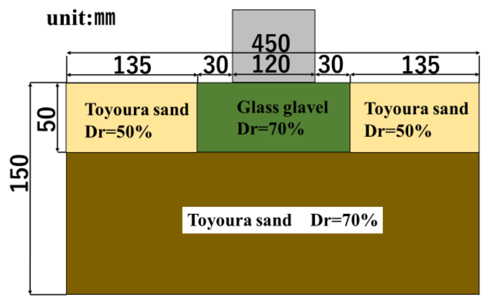

Fig.14 Case6 ; Glass gravel Dr=70%

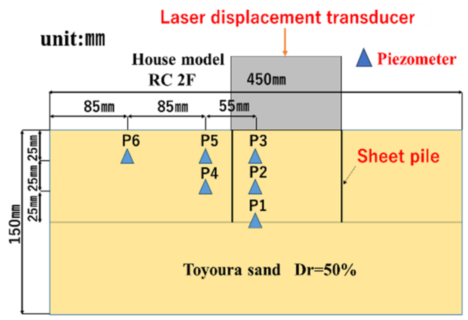

Fig.15 Case7 ; Sheet pile closing method

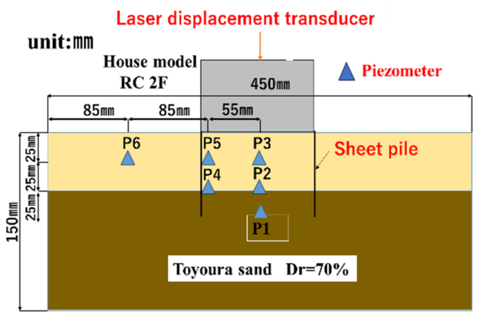

Fig.16 Case8 ; Sheet pile closing method

4. Experimental results and discussion

4.1 Excess pore water pressure ratio (Glass gravel improvement)

Fig.17 shows the excess pore water pressure ratio at point p3 in the ground directly under the residential area. When the excess pore water pressure ratio exceeds 0.5 (Dotted red line,), the bearing capacity in the ground begins to decrease, and when it exceeds 1.0 (Solid red line), complete liquefaction occurs (Nakazawa and Kanno (2013)).

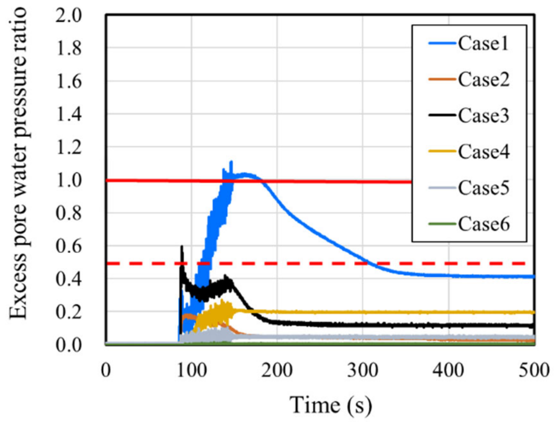

Fig.17 Excess Pore water pressure ratio at P3 (Glass gravel improvement)

In Case1, the excess pore water pressure ratio reached 1.0 and is completely liquefied. In Case 2, it is less than 0.2 and liquefaction did not occur. The reason for this is considered to be the high density of Case 2 (Dr=70%) and the influence of the building load.

In Case 3, the excess pore water pressure ratio reaches approximately 0.6, but in improved Case5 and Case6, it is suppressed to below 0.2. Also, in Case 4, the excess pore water pressure ratio is suppressed to about 0.2.

Fig.18 shows the excess pore water pressure ratio at point p6, which is outside the improvement area.

In Case 4, the excess pore water pressure ratio exceeds 1.0. In Case 4, no countermeasures were taken, so it is thought that the cause was the detached house sinking and the water level rising due to the occurrence of liquefaction, and the value exceeding 1.0 coincides with the water pressure remaining after the pore water pressure dissipated. In Case 5, it is about 0.75, and in Case 6, it is also about 0.6. This shows that by using Glass gravel with high water permeability in the improvement area directly under the detached house, the excess pore water pressure ratio can be suppressed and it is effective against liquefaction even outside the improvement area.

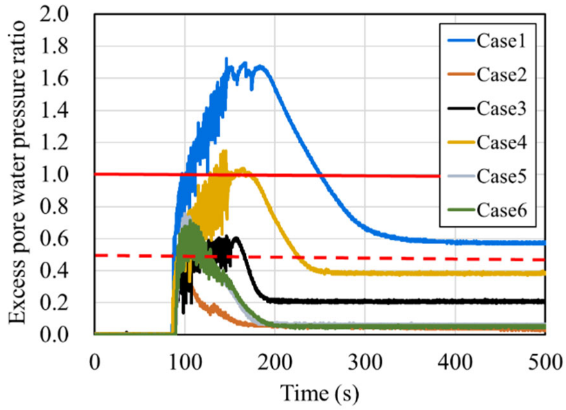

Fig.18 Excess Pore water pressure ratio at P6 (Glass gravel improvement)

4.2 Excess pore water pressure ratio (Sheet pile closing method)

Fig.19 shows the excess pore water pressure ratio at point p3 of the Sheet pile closing method.

In Case 7, the excess pore water pressure ratio reaches approximately 1.5, indicating complete liquefaction. The cause of this is thought to be that liquefaction occurred within the sheet piles and the building sank, but the pore water was not drained and the excess pore water pressure rose further. In Case 8, it is around 0.4, and liquefaction does not occur. The reason for this is thought to be that by embedding the sheet piles in a dense layer with Dr=70%, the seismic force applied to the ground within the sheet piles is reduced.

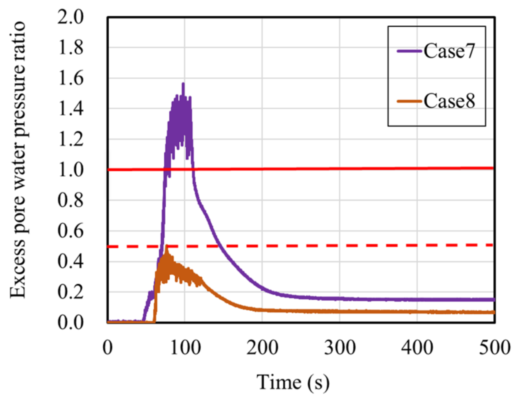

Fig.19 Excess Pore water pressure ratio at P3 (Sheet pile closing method)

Fig. 20 shows the excess pore water pressure ratio at point p6, which is outside the improvement range. At point p6 in Case 7, the excess pore water pressure ratio is close to 1.0. Also, at point p6 in Case 8, it is close to 1.0. This shows that when embedded in dense ground, it has an effect on liquefaction within the area of the sheet pile, but outside the area of the sheet pile, it behaves almost the same as normal untreated ground.

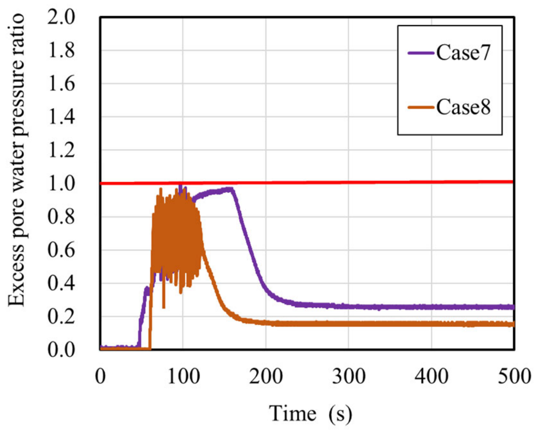

Fig.20 Excess Pore water pressure ratio at P6 (Sheet pile closing method)

4.3 Amount of settlement and slope

Fig.21 shows the time history in the amount of settlement of the detached house measured by a laser displacement meter, and **Table 3** shows the amount of settlement and inclination of the detached houses. As mentioned above, the allowable settlement amount is 80mm and the slope is less than 10/1000.

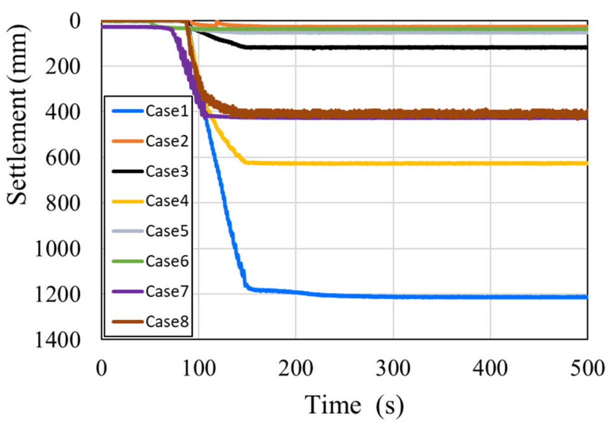

Fig.21 Amount of settlement of the detached house

Table 3. Settlement and inclination

Case	Settlement (mm)	Inclination
Case1	1210.0	33/1000
Case2	28.3	16/1000
Case3	120.0	25/1000
Case4	628.8	25/1000
Case5	54.7	8/1000
Case6	37.0	4/1000
Case7	427.7	41/1000
Case8	42.2	4/1000

In the untreated ground, Case 1 with Dr = 50% shows significant settlement, but in Case 2 with Dr = 70%, it is significantly suppressed. In addition, even in Case 3 where only the base of the ground has Dr=70%, settlement is suppressed to about 1/10 of Case 1. This shows that the denser the ground, the smaller the settlement of the residential land.

Next, we will compare the untreated ground and the surface improvement. Comparing Case 1 with Case 4, where the base of the ground is Dr=50%, the inclination is almost the same, but the amount of settlement is suppressed to about half, from 1210 mm to 628.8 mm.

Furthermore, we compare case2, case5, and case6 with Dr=70%. It can be seen that the amount of settlement is within the allowable amount of settlement 80mm in all cases. On the other hand, the inclination was suppressed to less than the allowable value of 10/1000 in Case 5 and Case 6 where the surface layer was improved with Glass gravel. From these results, it can be seen that by improving the surface layer with Glass gravel on dense ground with a foundation of Dr = 70%, both settlement and inclination are kept within the allowable values, and there is a liquefaction suppressing effect.

Finally, we will discuss the Sheet pile closing method. Comparing Case 1 with Case 7, inclination has increased, but the amount of settlement was suppressed to about 1/3. In Case 8, where the excavations were conducted, both the amount of settlement and inclination were suppressed, and they were within the allowable values. This shows that the Sheet pile closing method has the effect of suppressing settlement, and in particular, when it is embedded in a dense bedrock layer with Dr=70%, it has a significant effect of suppressing both the amount of subsidence and inclination.

5.Concluding remarks

In this study, we investigated the suppression of liquefaction by using Glass gravel and Sheet pile closing method to dissipate excess pore water pressure under the surface layer of detached house.

The results of this study indicate that replacing the liquefaction layer on the surface of untreated ground with highly permeable Glass gravel is effective against liquefaction by dissipating pore water during earthquakes. In addition, by improving the surface layer of the ground with dense foundations using Glass gravel, both settlement and inclination were kept within allowable values, indicating that the countermeasures were highly effective.

In the Sheet pile closing method, it was observed that embedding them helps excessive pore water pressure inside the sheet piles could be suppressed, which had the effect of suppressing settlement and tilting.

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