Fundamental research on liquefaction countermeasures for double steel sheet pile quay walls using permeable sandbags

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ABSTRACT

The 2011 off the Pacific coast of Tohoku Earthquake prompted the development of earthquake-resistant port facilities. Port facilities not only mitigate damage in the event of a disaster, but also provide a base for reconstruction work and an economic foundation for the fishing industry, thus requiring rapid and rational maintenance. The authors focused on the liquefaction of soil filled with double steel sheet pile quay walls, and verified countermeasures using sandbags filled with highly permeable gravel and permeable steel sheet piles to reduce excess pore water pressure in the ground through centrifuge model experiments. The experimental results showed that the drainage effect of the sandbags suppressed the generation of excess pore water pressure, and that the permeable steel sheet piles shortened the dissipation time of the excess pore water pressure. The replacement of the liquefied layer with sandbags was also found to deter sheet pile deformation by increasing the ground bearing capacity behind the sheet piles.

Key words: *liquefaction, permeable sandbag, double steel sheet pile, centrifugal model test*

1. Outline of the project

1.1. Background

The 1995 Southern Hyogo Prefecture Earthquake damaged port facilities at 24 ports in the Hanshin-Awaji area. According to a report by the Port and Harbor Engineering Research Institute (1997), liquefaction is cited as one of the causes of large displacements of quay walls and seawalls.

The 2011 off the Pacific coast of Tohoku Earthquake affected all ports on the Pacific coast from Hachinohe Port in Aomori Prefecture to Kashima Port in Ibaraki Prefecture, causing major damage to quays and other areas.

According to a report by the Ports and Harbors Bureau of the Ministry of Land, Infrastructure and Transport (2012) , port facilities were mainly damaged by the tsunami, but there were many reports of liquefaction damage from Soma Port to Ibaraki Port to the south. After the earthquake, it took two years to restore the functionality of the damaged port facilities. However, there was no damage to the earthquake-proof berth, such as collapse, and it played a major role in transporting emergency relief supplies and securing regional logistics immediately after the earthquake.

In recent years, a huge Nankai Trough earthquake is expected to occur, but it is difficult to provide land support after the earthquake in the Shikoku region Nishida (2017). In addition, small-scale quays such as fishing port quays are the livelihood infrastructure of local residents during normal times, and should be used as bases for relief activities and subsequent recovery and reconstruction activities in the event of the Great Nankai Trough Earthquake. Therefore, the development of earthquake-proof quay walls and countermeasures for liquefaction are urgent issues Goto et al. (2019).

1.2. Objective of the project

In order to carry out this research, we drew up an experimental plan with reference to the following literature on quay wall reinforcement and liquefaction countermeasures.

Ise et al. (2018) and Hyodo et al. (1999) conducted research on suppressing lateral flow behind quay walls due to liquefaction. Their work demonstrates that resistance to horizontal displacement by shear walls and pore water pressure dissipation at the back of the quay are effective against the increase in earth pressure due to liquefaction during earthquakes.

Furuichi et al. (2015) investigated the seismic and tsunami-resistant performance of an embankment with a double steel sheet pile structure. The rigidity and strength of the steel sheet piles function help suppress deflection of the sheet piles and deformation of the embankment body, but the high water-stopping properties indicate that excess pore water pressure within the filler soil is not dissipated.

Tanaka et al. (1996) investigated the development of liquefaction countermeasure construction methods using steel materials with drainage functions. It is reported that the deformation of the sheet piles is reduced by suppressing liquefaction of the ground around the sheet piles and maintaining their strength.

Matsuoka (2004), Matsuoka et al. (2020) proposed ground improvement that drains water from the ground by using permeable sandbags. It is reported that the integration of sandbags increases the bearing capacity of the ground, suppresses liquefaction as a permeable layer, and reduces ground vibration.

The authors developed a countermeasure using sandbags and permeable steel sheet piles to reduce excess pore water pressure in the ground against liquefaction in the soil filling of double steel sheet pile quays for small-scale quays such as fishing ports.

2. Experimental method

2.1 Experiment overview

In this study, we used a dynamic centrifuge and conduct an investigation at a centrifugal acceleration of 40G. **Fig. 1** shows a photo of the experimental model for Case3 (before the experiment).

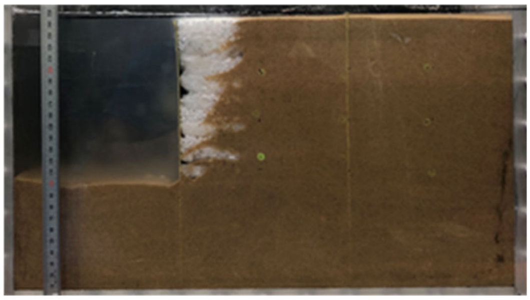

Fig. 1 Photo of the experimental model for Case 3 (before the experiment).

Fig. 2 shows the experimental model for the study case. In this study, we conducted three cases. Case 1 is a

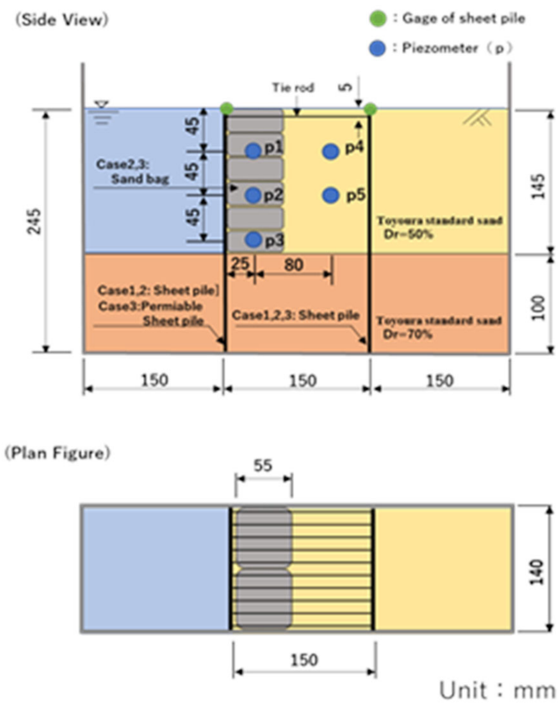

Fig.2 Experimental model for the study case

double steel sheet pile type quay wall, Case 2 is a double steel sheet pile type structural wall, with part of the fill soil at the back replaced with sandbags containing gravel soil, Case 3 where the front sheet pile of Case 2 is substituted with permeable steel.

Pore water pressure gauges p1 to p3 are installed in the sandbag, and p4 and p5 are installed in the unmeasured area to measure the pore water pressure in the ground. In addition, the displacement of the sheet pile is measured from the gauge point of the sheet pile.

Fig.3 shows the hole arrangement of permeable steel sheet piles. Based on a study by Tanaka et al. (2005) on the water permeability properties of permeable steel sheet piles, the permeable steel sheet piles used in the experiment had a hole diameter of 1.5 mm, a hole spacing of 12.5 mm, and an open area ratio of 0.57%.

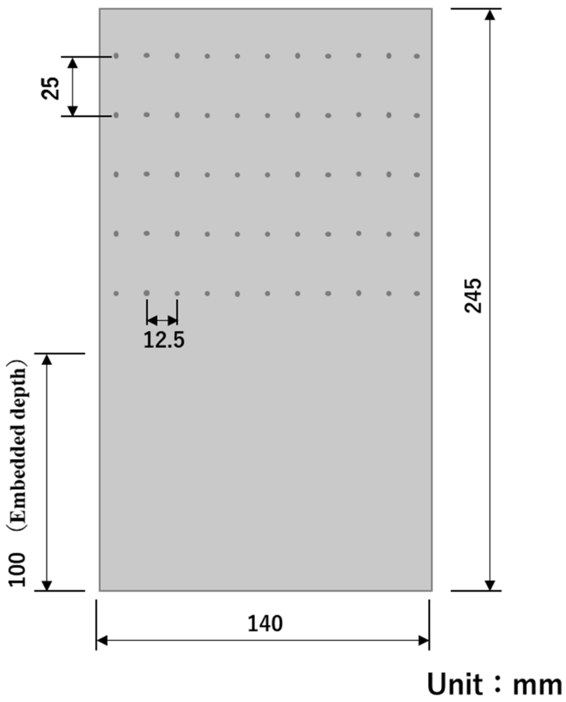

Fig.3 Hole arrangement of permeable steel sheet pile

Fig. 4 illustrates the particle size accumulation curve of the ground material used in the experiment. The ground material used for the soil layer is Toyoura standard sand (Gs = 2.640, e_{max} = 0.973, e_{min} = 0.609), the base layer is made by the aerial drop method with a relative density of 70%, and the liquefied layer is made by the underwater drop method. After reducing the relative density to 50%,

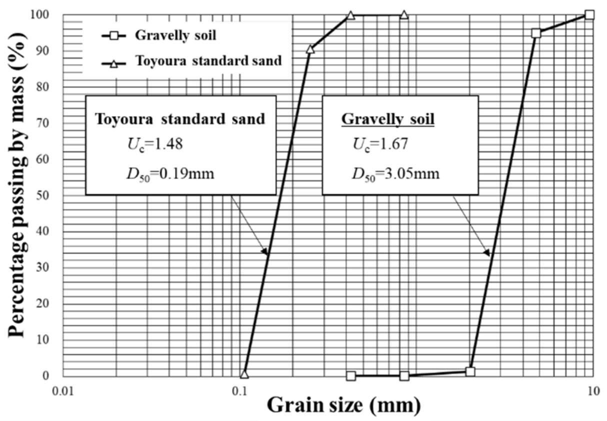

Fig.4 Grain size accumulation curve of the ground material used in the experiment

it was saturated with an aqueous methylcellulose solution, which has a viscosity 40 times that of water. The model sandbags were made of gravelly soil (Gs=2.849, e_{max}=0.653, e_{min}=0.489) and packed in a nonwoven fabric pack to give a relative density of 70%.

Toyoura standard sand has a hydraulic conductivity k = 1.00 × 10^{-4} m/s, and gravel soil has a hydraulic conductivity k = 2.58 × 10^{-2} m/s. Filling permeable sandbags with gravelly soil can be expected to drain excess pore water pressure.

(1) Shaking table acceleration

Fig. 5 shows the acceleration of the shaking table used in the experiment. Based on the liquefaction simple determination method (FL value method) of the Road Bridge Specifications (2017), the shaking table acceleration at which the liquefaction layer will definitely liquefy is set.

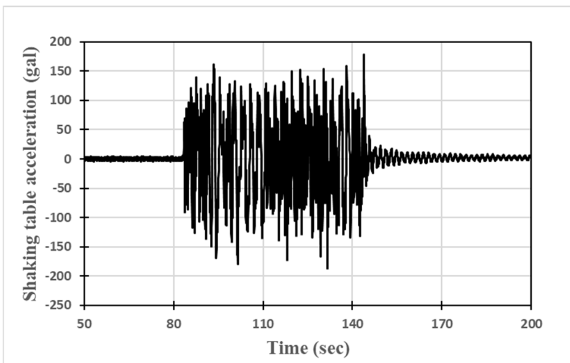

Fig.5 Shaking table acceleration used in the experiment

3. Experimental results and discussion

3.1 Deformation of sheet piles

Fig.6 shows the displacement of the quay before and after the experiment. In Case 1, where no countermeasures were taken, the front sheet piles protruded significantly in the horizontal direction, and the counterfort sheet piles were also deformed.

In Case 2, which uses sandbags, the protrusion of the front sheet pile is reduced compared to Case 1, and the deformation of the counterfort sheet pile is also reduced accordingly. Similar to Case 2, Case 3, which uses sandbags and permeable steel sheet piles, suppresses deformation and maintains the shape of the quay wall.

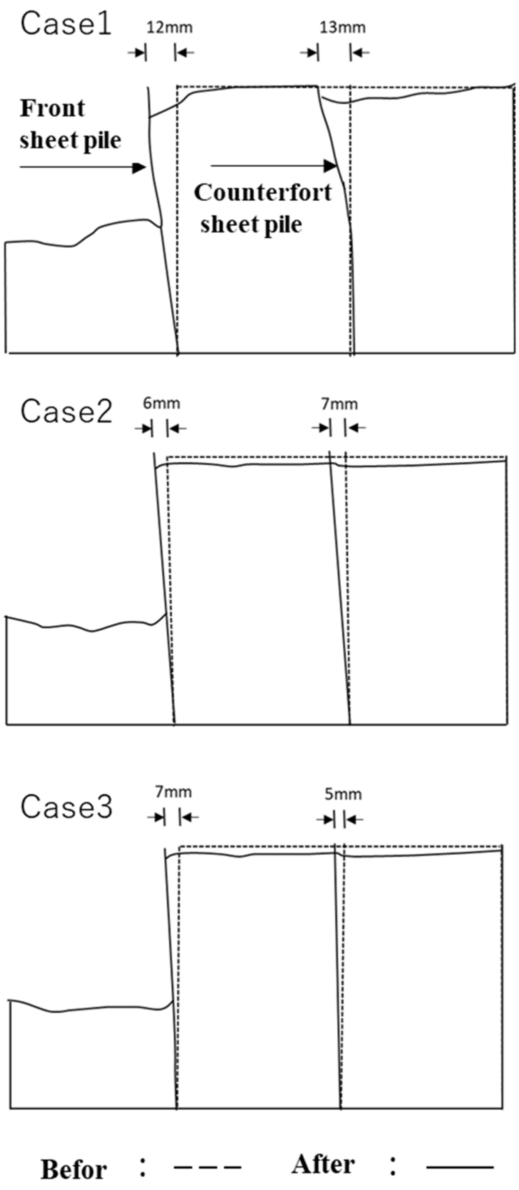

Fig.6 Displacement diagram of the quay before and after the experiment

Table 1. shows the final deformation of the sheet pile. It can be seen that both the front sheet pile and counterfort sheet pile suppress the deformation of the sheet pile by about 6 mm compared to Case 1 where no countermeasures were taken. However, in Case 2 and Case 3, there was no significant difference in the amount of deformation between the front sheet pile and the counterfort sheet pile.

These deformation results confirmed that the amount of deformation of the sheet piles was suppressed by using sandbags. This is thought to be because replacing the liquefied layer with sandbags maintained the supporting capacity of the ground behind the sheet piles, which led to suppression of sheet pile deformation.

Table1. Final deformation amount of sheet pile

			unit：mm
	Case1	Case2	Case3
Front sheet pile	12	6	7
Counterfort sheet pile	13	7	5

3.2 Excess pore water pressure

Fig.7 to **Fig. 9** show comparison diagrams of Case 1 to Case 3 at each excess pore water pressure (points p1 to p3) of the filled soil in the sandbag installation area.

At point p1, excess pore water pressure exceeds the initial effective stress and liquefaction occurs in untreated Case 1. In Case 2 and Case 3, the excess pore water pressure is significantly reduced, and it can be seen that only the variation in pore water pressure caused by the vibration component during excitation occurs.

In addition, at points p1, p2, and p3, the excess pore water pressure in Case 3 dissipates about 20 seconds faster than in Case 2, confirming that the permeable steel sheet pile facilitates the dissipation of excess pore water pressure.

However, there is almost no difference in the amount of sheet pile deformation between Case 2 and Case 3, indicating that the promotion of dissipation of excess pore water pressure has almost no effect on suppressing sheet pile deformation.

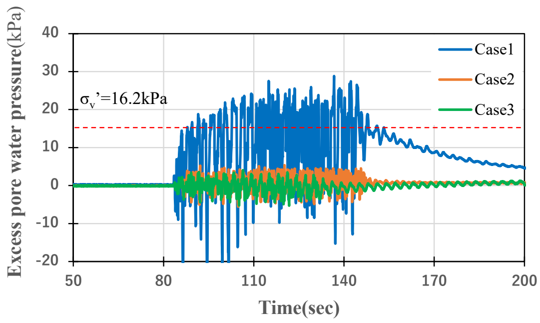

Fig.7 Excess pore water pressure at point p1

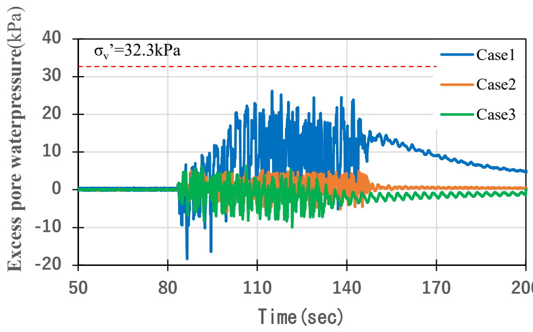

Fig.8 Excess pore water pressure at point p2

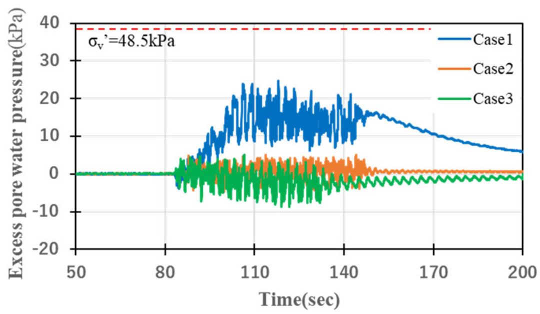

Fig.9 Excess pore water pressure at point p3

Fig. 10 and **Fig.11** show comparison diagrams of Cases 1 to 3 at each excess pore water pressure (points p4 and p5) of filled soil without sandbags.

At point p4, liquefaction occurs in Case 1 because the excess pore water pressure exceeds the initial effective stress σv'. However, in Case 2 and Case 3, the excess pore water pressure is reduced compared to Case 1. Similarly, at point p5, the excess pore water pressure decreases in Case 2 and Case 3. This is thought to be due to excess pore water pressure being drained to the ground surface by the sandbags even at locations where no sandbags were installed.

Also, when paying attention to the dissipation of excess pore water pressure, Case 3 dissipates the excess pore water fastest at around 130 seconds.

On the other hand, in Case 1, the excess pore water pressure does not dissipate even around 200 seconds, and in Case 2, the excess pore water pressure dissipates around 170 seconds. Therefore, it can be seen that the permeable steel sheet pile has a high effect of dissipating excess pore water pressure at these points as well.

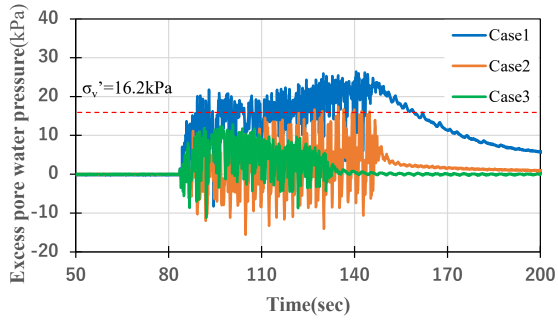

Fig.10 Excess pore water pressure at point p4

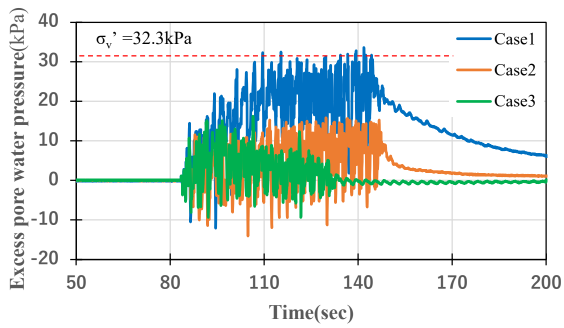

Fig.11 Excess pore water pressure at point p5

Therefore, by installing sandbags, excess pore water pressure is reduced even in the filled soil in the double steel sheet piles on the back of the sandbags, so it is thought that it is possible to suppress the reduction in the bearing capacity of the ground during an earthquake.

On the other hand, a study that examined the relationship between excess pore water pressure ratio (excess pore water pressure divided by initial effective stress) and volumetric strain using cyclic undrained triaxial tests were conducted by Nakazawa and Kanno (2013). They found that volumetric strain increases from excess pore water pressure ratio of 0.5 and begins to increase rapidly when it exceeds 0.8.

Therefore, in the case where sandbags are used, excess pore water pressure is reduced to less than 50%, which makes it possible to suppress ground displacement such as lateral flow, and suppress deformation of sheet piles.

4. Concluding remarks

In this study, we investigated the suppression of sheet pile deformation and liquefaction by using sandbags and permeable steel sheet piles to dissipate excess pore water pressure in the filling soil of a double steel sheet pile type quay. As a result, we found the following.

It was confirmed that in untreated double steel sheet pile type quays, excess pore water pressure in the filler soil increases in the surface layer, leading to liquefaction and significant deformation of the sheet piles.

It was confirmed that by using permeable sandbags, the excess pore water pressure in the filler soil was significantly reduced, maintaining the supporting capacity of the surrounding ground by suppressing liquefaction, and the deformation of the sheet piles was reduced.

In addition, even in the filled soil outside the sandbag installation area, the drainage effect of the sandbags was observed to reduce excess pore water pressure in the surrounding area.

It was confirmed that the use of permeable steel sheet piles shortens the dissipation time of excess pore water pressure in the ground. However, it was noted that the dissipation time of excess pore water pressure had little effect on suppressing sheet pile deformation.

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