EFFECTIVENESS OF THE SHEET PILE WALL AGAINST HOUSE SUBSIDENCE AND INCLINATION INDUCED BY LIQUEFACTION

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Abstract

The sheet pile wall method, a countermeasure against house subsidence and inclination induced by liquefaction, is proposed in this paper.Though a number of countermeasures against liquefaction had been proposed, few have been applied to residential housings. After the 2011 Tohoku Earthquake in Japan, a lot of residential housings had been damaged by liquefaction on that occasion, demand for the reinforcement against liquefaction, especially for the existing buildings, became apparent.The proposed method consists of the installation of short length sheet pile wall around the house foundation. Thus, this method is suitable to apply to existing housings, economically. Characteristics and advantages of this method are as follows. 1) The method is intended to prevent the house foundation ground movement due to liquefaction, however, occurrence of liquefaction is allowed. 2) The sheet piles are not reached at non-liquefiable layer existing under the liquefiable layer. It means the sheet piles are not intended to support the housing load. 3) The method is able to construct in dense residential areas. The shaking table model tests, under the gravitational (1g) and the centrifugal (40g) field, were conducted to investigate effectiveness of proposed countermeasure in terms of sheet pile wall length around house foundation. The results indicated it is able to reduce the house subsidence and inclination by using the sheet pile wall. Influence of the length of sheet pile wall in terms of house subsidence and inclination was also clarified. In addition, effective stress analyses were conducted under various ground conditions and sheet pile length. According to these results, the same effectiveness of the sheet pile wall as the model tests is also confirmed.

Keywords: Liquefaction, Countermeasure, Sheet pile wall, Centrifugal shaking table test, Effective Stress Analysis

1. Introduction

The severe liquefaction damages were occured in wide spread area nearby river and coast by 2011 Tohoku earthquake [1]. Especially, in Urayasu city, Chiba prefecture, which is located approximetelly 400 km away from the epicenter of the earthquake, a lot of residensial housing damages had been observed induced by liquefaction [2] . It was considered that direct cause of the damage was the two-minuets-duration ground shake, of which the maximum ampritude was only about 150 cm/s^2 [3]. On the other hand, the main factor of severe damage was considered that damaged houses had constructed without sufficient consideration on soil liquefaction.

Though a number of countermeasures against liquefaction had been developed [i.g. 4] in Japan since 1964 Niigata earthquake, few have been applied to residential housings. Therefore, after the 2011 Tohoku Earthquake in Japan, demand for the countermeasure against liquefaction, especially for the existing buildings, became apparent.

The sheet pile wall method for reducing house subsidence and inclination induced by soil liquefaction is proposed in this paper. The proposed method consists of short length sheet pile wall installed around the house foundation. Thus, it is suitable to apply to existing housings economically. Shaking table tests and effective stress analyses were conducted to examine effectiveness of proposed method.

2. Sheet Pile Wall Method and Investigation Condition

Fig. 1 illustrates the proposed method. Sheet pile wall is formed by installing shallow steel sheet piles around house foundation. Characteristics and advantages of this method are following.

1) The method is intended to prevent the movement of liquefied foundation ground under the house in horizontal direction. Due to existence of the wall, it is able to reduce the house subsidence and inclination.

2) The sheet pile wall does not reach the base layer existing under the liquefiable soil layer. Thus, the sheet pile wall is not intended to support the housing load. In addition, using short length sheet pile saves material cost.

3) Because of simple construction way, the method is suitable to apply to existing housings even in dense residential areas.

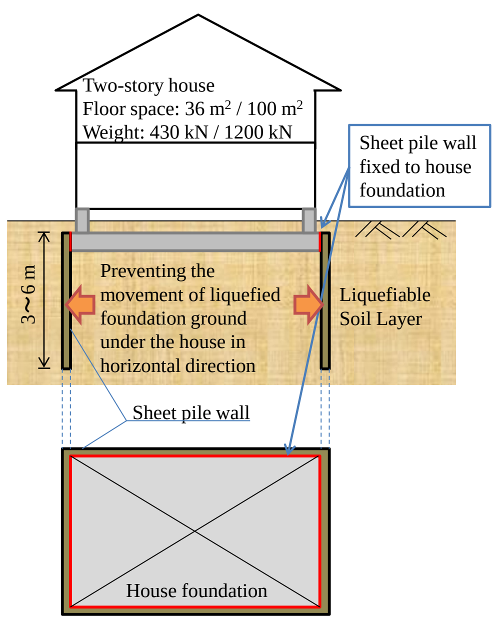


Fig. 1 – Sheet pile wall method against damage of houses induced by liquefaction

Fig. 2 shows typical ground condition of Urayasu city, utilized in this study. FL-values, potential of liquefaction at individual layer, were calculated, in accordance with the method of the highway bridges of Japan [5], with two earthquake ground motions and compared. The one was the ground motion of 2011 Tohoku earthquake, the maximum amplitude of α_{max}=150 cm/s^2, observed in Urayasu. The other was the predicted motion; α_{max}=300 cm/s^2, of the northern Tokyo Bay earthquake. When FL-value is less than 1.0, the target layer can be estimated as liquefiable layer. According to this estimation method, it was estimated total thickness of liquefiable soil layer to be about 2 m by the Tohoku earthquake, about 9 m by the northern Tokyo Bay earthquake. It means that more severe soil liquefaction and damages can be predicted at coastal areas such as Urayasu city in future. Thus, thickness of liquefiable soil layer of the model ground was chosen as 9.0 m.

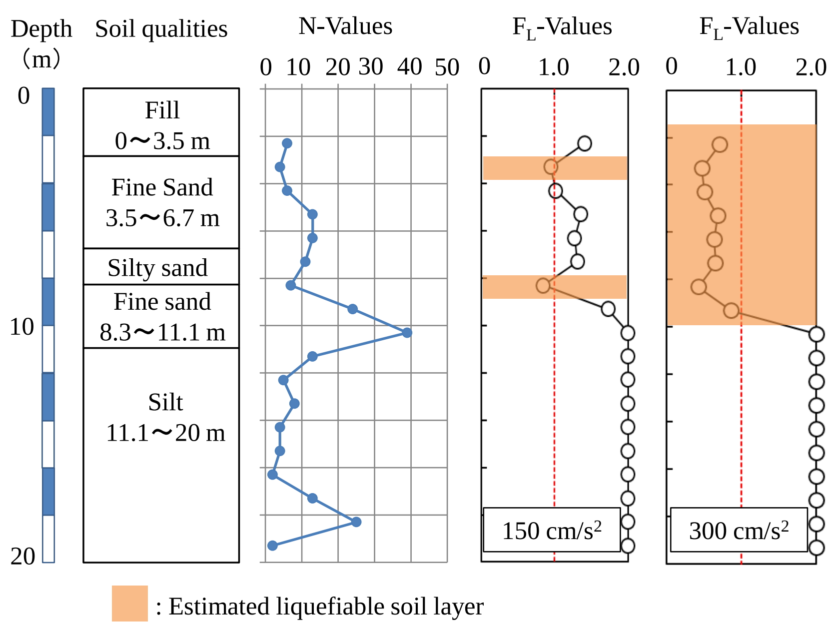


Fig. 2 – Evaluation of liquefaction potential at target ground in Urayasu city

3. Shaking Table Test on Effectiveness of Sheet Pile Wall Method

Gravitational (1g) and centrifugal (40g) shaking table tests were conducted as shown in Table 1. The purpose of these tests was to examine the influence of sheet pile length and/or fixing condition between house foundation and sheet pile wall on effectiveness of reducing house subsidence and inclination. The length of sheet pile wall was varied from 0 to 9 m, i.e. 0, 3, 6, and 9 m, in which 0 m means house without-countermeasure. Fixed and Free in Table 1 mean fixing conditions between house foundation and the sheet pile wall.

The scaling laws between prototype and gravitational test model or centrifugal test model are shown in Table 2.

Fig. 3 illustrates aluminum housing model. In order to induce house inclination, the half of housing floor space was made to two stories and the other part was made to one story. As mentioned above, there were two fixing conditions between house foundation and sheet pile wall, i.e. the wall fixed to house foundation with aluminum angle plate (Fixed case; hereafter) or free from house foundation (Free case; hereafter). In either fixing conditions, polyurethane fillings were plugged in the space between house foundation and the sheet pile wall in order to prevent leakage of liquefied soil from foundation ground under the house.

The floor dimensions and the average vertical pressure of the house, and bending stiffness of the sheet pile wall, between prototype and models are shown in Table 3 and 4.

Table 1 – Test cases to examine effectiveness of sheet pile wall method

Case	Test condition	Input acceleration	Model type((Length of sheet pile wall) / (Thickness of liquefiable soil))			
		cm/s^2	0 (non-countermeasure)	1/3	2/3	1
G1	Gravitational test (1g)	150	○	○ (Fixed)	-	-
G2		150	○	○ (Free)	-	-
G3		150	○	-	○ (Fixed)	-
G4		150	○	-	○ (Free)	-
G5		150	○	-	-	○ (Fixed)
C1	Centrigugal test (40g)	150	○	○ (Fixed)	○ (Fixed)	-
C2		300	○	○ (Fixed)	○ (Fixed)	-

○; Conducted, Fixed; Ground wall fixed house foundation, Free; Ground wall free from house foundation.

Table 2 – Scaling Law of These Tests

	Gravitational (1g) Test	Centrifugal (40g) Test
Length	1/20	1/40
Density	1	1
Stress	1	1
Time	1	1/40
Vibraton frequency	1	40
Coefficient of permeability	1	40
Bending stiffness	$1/20^4$	$1/40^4$

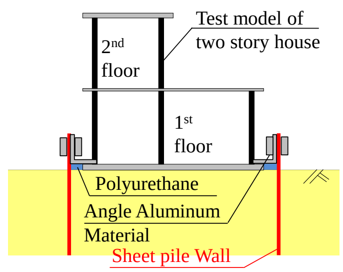


Fig. 3 – Test model of the house

Table 3 – Floor spaces and ground pressures of the house

	Prototype			Model		
	Floor Space	Mass	Vertical Pressure	Floor Space	Mass	Vertical Pressure
	m^2	kg	kN/m^2	mm^2	kg	kN/m^2
Gravitational Test	6 x 6	4.40×10^4	12.0	300 x 300	6.40	0.7
Centrifugal Test	10 x 10	1.22×10^5	12.0	250 x 250	1.80	11.3

Table 4 – Similarity ratio of bending stiffness between prototype of a sheet pile wall and model of the wall

	Prototype		Model			Bending Stiffness Ratio (B.R.)	Schaling Law (S.L.)	Simirality ratiio
	Material	Bending Stiffness EI_p	Material	Thickness	Bending Stiffness EI_m	EI_m / EI_p		(B.R.) / (S.L.)
	-	kN･m^2/m	-	mm	kN･m^2/m	-	-	-
Gravitational Test	Steel	8.52×10^2	Aluminum	2.5	9.11×10^{-2}	1.07×10^{-4}	$^*1/20^3$	0.85
Centrifugal Test				1.0	5.83×10^{-3}	6.84×10^{-6}	$^*1/40^3$	0.43

*Scaling low of bending stiffness is $1/20^4$ or $1/40^4$ discrived in Table 2 In this table, however, these numbers are different, because EI means bending stiffness per unit width.

3.1 Gravitational (1g) Shaking Table Test

Fig. 4 represents a 1/20 scale model of ground and houses for gravitational test (G3). The surface of model ground; non-liquefiable soil layer, and liquefiable soil layer were made of silica sand No.7 (G_s=2.645, e_{max}=1.234, e_{min}=0.730) as 60 % relative density. The non-liquefiable layer existing under the liquefiable soil layer was made of gravel. Two house models, house without-countermeasure and house with-countermeasure, were set on the surface of the model ground. Settlements of houses were measured by laser displacement transducers. In addition, pore water pressure transducers were installed in model ground.

Five gravitational tests shown in Table1 were conducted under the same ground condition and sensor locations as mentioned above.

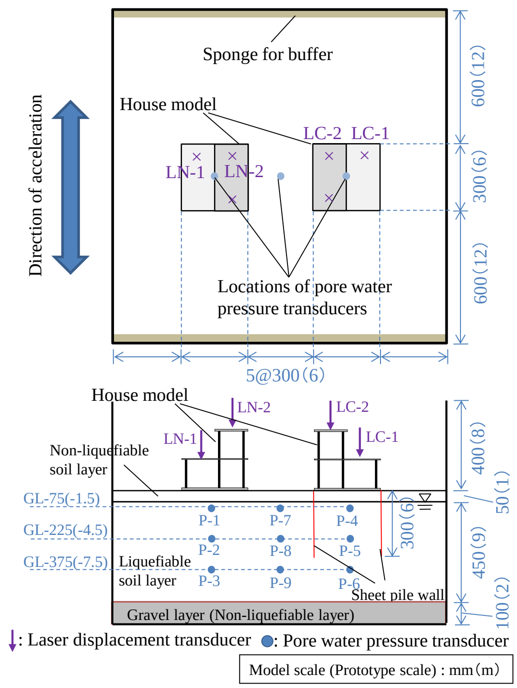


Fig. 4 – Model ground and sensors for gravitational test (G3)

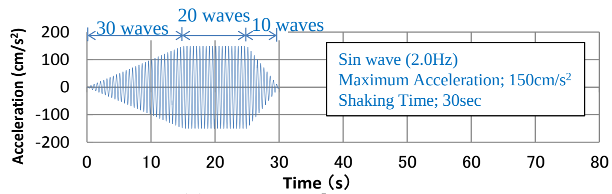
Fig. 5a represents acceleration time history of input motion of gravitational shaking table tests. The same motion was applied to the model ground only once in each test.

Representative time histories of excess pore water pressure ratio of ground at GL-75 mm, and subsidence of houses, are shown in Fig. 5b and 5c. These data were measured in test G3. Excess pore water pressure ratio was calculated by dividing the excess pore water pressure in effective stress at installation depth of the water pressure transducer. Incidentally, the effective stress of the house foundation ground (at P-1 and P-4) took into account of the house load.

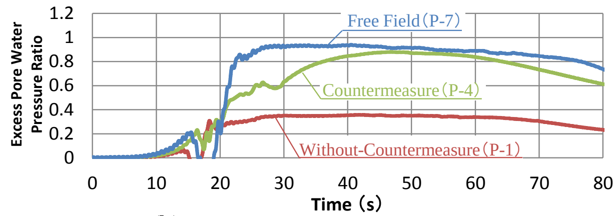
It is found that pore water pressures at three locations (P-1, P-4, and P-7) were increasing about 10 s after the shake event start. Both excess pore water pressure ratio of the free field (P-7) and the house foundation ground surrounded by sheet pile wall (P-4) reached at 1.0. On the other hand, judging from P-1 data, the foundation ground of the house without-countermeasure seemed not to be liquefied. From Fig. 5c, however, it is conformed that the subsidence of house with countermeasure (LC-1 and LC-2) is smaller than that of the house without-countermeasure (LN-1 and LN-2). In addition, the differential subsidence between 2nd floor and 1st floor of the house with sheet pile wall is smaller than that of without the wall. It means that house inclination was also reduced by sheet pile wall.

According to these results, it is found that even though excess pore water pressure ratio at P-1 did not reach at 1.0, subsidence and inclination of the house without-countermeasure were more severe than that of the counter-measured. This can be explained as bellow.

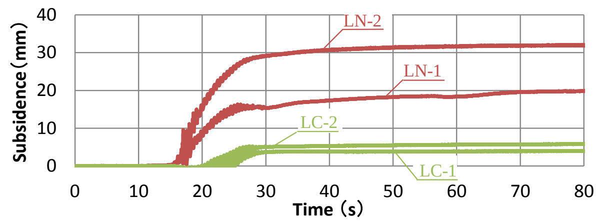
Excess pore water pressure of P-1 increased at time 10 s-20 s after the shake event start. At that time, vertical displacements of the house (LN-1 and LN-2) also increased rapidly. When the house sunk down, it is considered that volume stretch occurred due to the lateral flow of the house foundation ground in horizontal direction. Because of positive soil dilatancy of the foundation ground, increase of the excess pore water pressure of P-1 after 20 s was obstructed.



(a) Input acceleration motion



(b) Excess pore water pressure ratio



(c) Subsidence of houses

Fig. 5 – Experimental results of gravitational test (G3)

3.2 Centrifugal (40g) Shaking Table Test

Fig. 6 represents a 1/40 scale model of ground and houses for centrifugal test (C1 and C2). The surface of model ground; non-liquefiable soil layer, was made of the silica sand No.4 (G_s=2.640, e_{max}=1.047, e_{min}=0.692) as 50 % relative density. The liquefiable soil layer was made of the silica sand No.7 (G_s=2.645, e_{max}=1.234, e_{min}=0.730) as 60 % relative density. The non-liquefiable layer existing under the liquefiable soil layer was made of soil cement (q_u=1000 kN/m^2). The 40x10^{-3} Pa· s viscosity methylcellulose solution was used as pore liquid in order to satisfy scaling law of the permeability. Three house models; a house without-countermeasure and two countermeasured houses, were set on the surface of model ground. Pore water pressure transducers were installed in model ground and the vertical displacements of house were measured by laser displacement transducers.

In centrifugal tests, amplitude of input acceleration motion was different between C1 and C2 as shown in Table1, but time history of the motion was the same. C2 test was conducted under the condition the model ground had been experienced the 150 cm/s^2 motion (C1 test). It means ground and house condition before C2 test were different from initial condition before C1 test.

Fig. 7a represents time history of input motion of C2 test, and C2 test results; time history of excess pore water pressure ratio and subsidence of houses, were shown by Fig. 7b and 7c. Incidentally, calculation method of the excess pore water pressure ratio is the same of gravitational test. Fig. 7b shows time history of excess pore water pressure ratio at GL-1.5 m. It is found that pore water pressures at three locations (P-1, P-4, and P-7) started increasing about 70 s after the shake event start. Excess pore water pressure of free field (P-7) reached at 1.0 after the occurrence of the maximum acceleration. On the other hand excess pore water pressure ratio of the foundation ground of the house without-countermeasure (P-1) and with the sheet pile wall method (P-4) did not reach at 1.0, as previously explained as gravitational test.

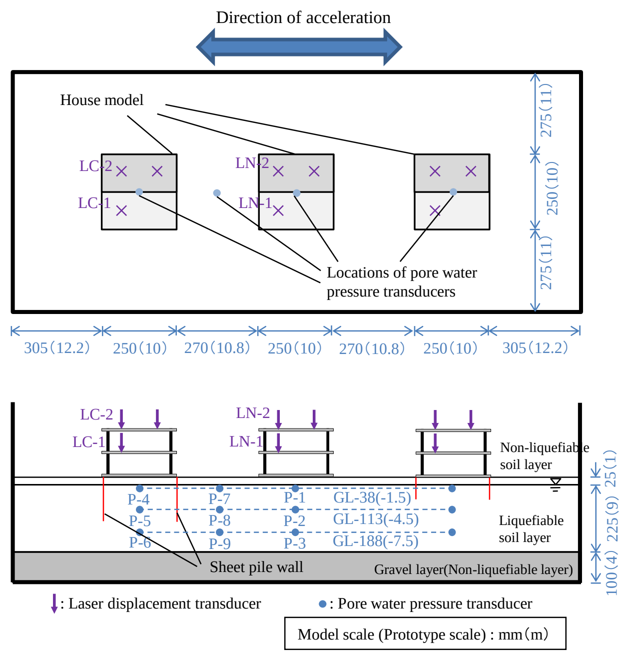


Fig. 6 – Model ground and sensors for centrifugal test (C1 and C2)

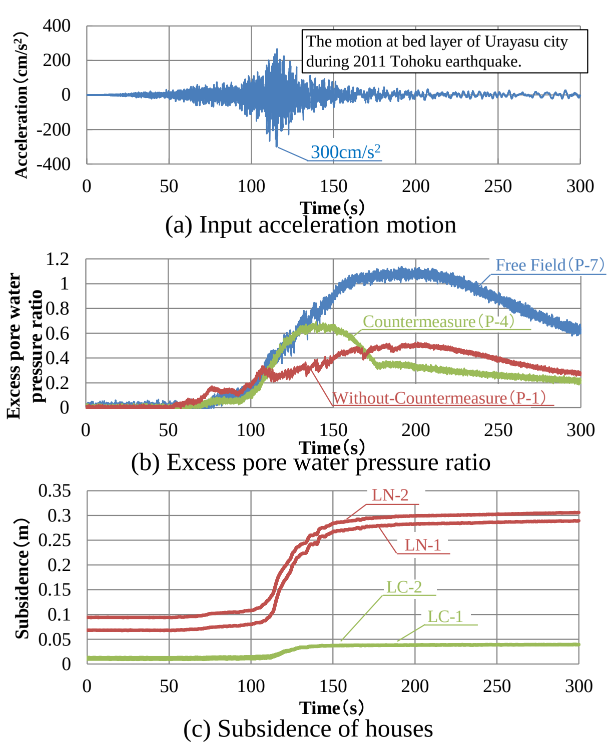


Fig. 7 – Experimental results of centrifugal test (C2)

Response of P-4 can be explained that the water pressure of the ground surrounded by the sheet pile wall leaked to outside of the wall at about 120 s after the shake event had started.

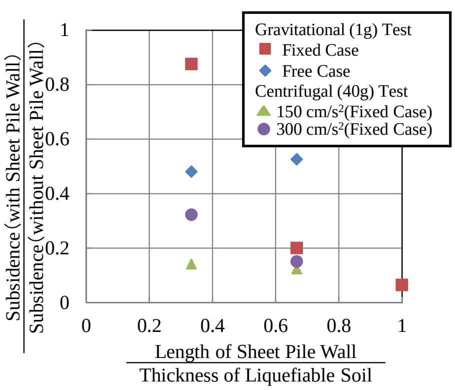
From Fig. 7c, the subsidence of house with sheet pile wall (LC-1 and LC-2) is smaller than that of the house without-countermeasure (LN-1 and LN-2). Here, subsidence at 0 s is residuals resulted from C1 test. The differential subsidence between 2nd floor and 1st floor of the house with-countermeasure is smaller than that of without-countermeasure. Therefore, in terms of house subsidence and inclination, same effectiveness of the sheet pile wall method is confirmed as the gravitational tests.

3.3 Effectiveness of Sheet Pile Wall Method

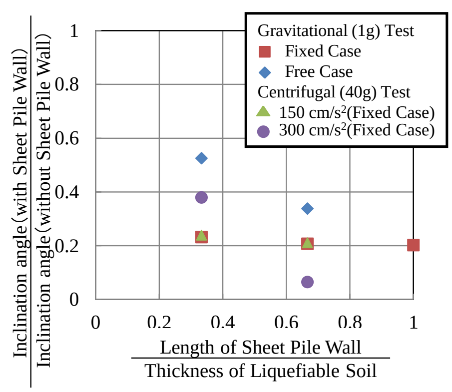
Fig. 8a and 8b summarize the experimental results of gravitational and centrifugal shaking table tests. The horizontal axis is the ratio of the length of the sheet pile wall to the thickness of liquefiable layer. The vertical axis is the ratio of final subsidence or inclination of the model houses with the sheet pile wall to that of without the wall.

It is found that as longer the wall installed around house foundation, more effectiveness appeares on house subsidence and inclination. It is found that if there is sheet pile wall with length longer than one-third the liquefiable soil thickness, house subsidence and inclination are reduced by less than half of that without the wall. Especially, regarding centrifugal test results, the wall was able to reduce the house deformation by about one-fifth to one-third that without the wall.

In addition, regarding fixing condition, inclination of the Fixed case house less than that of the Free case. It sugests that the Fixed case has the resistance against house inclination due to the reaction force acting from ground during house leaning.



(a) Subsidence



(b) Inclination angle

Fig. 8 – Shaking table test results on effectiveness of the sheet pile wall against house deformations

4. Dynamic Effectiveness Stress Analysis on Effectiveness of Sheet Pile Wall Method

Dynamic effective stress analyses were conducted to examine effectiveness of sheet pile wall method at actual ground conditions. O-EFECT [6]; the computer program based on the effective stress theory, was utilized for the analyses. Both multi-dimensional consolidation equation proposed by Bio [7] and constitutive model for sand proposed by Matsuoka [8] were adopted in the program.

Firstly simulation of centrifugal test was conducted to confirm the applicability of the program for this study. Then, estimations of effectiveness of proposed countermeasure for actual ground conditions were conducted.

4.1 Simulation of Centrifugal Shaking Table Test

Fig. 9 represents two-dimensional model for effective stress simulation of centrifugal shaking table test. Ground and house were modeled by solid elements, and the sheet pile wall was modeled by beam elements. Because of two-dimentional model, the wall in parallel direction of the page was modeled by springs. Due to the deformation of the side wall is important, only the axial stiffness of the parallel wall regard to the horizontal direction was considered.

The analitical paramaters were set in regard to soil element test results as shown in Table 5.

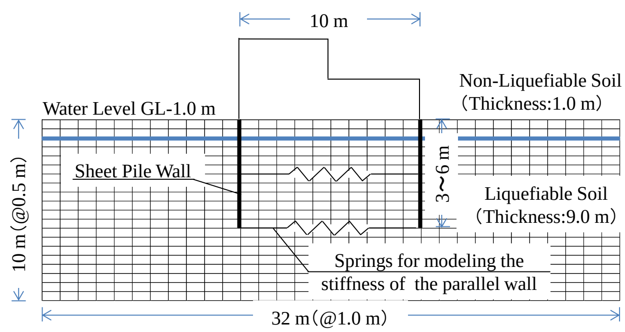
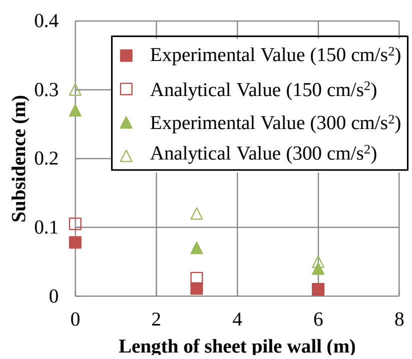


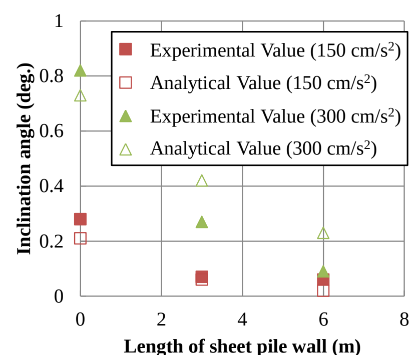
Fig. 9 – Effectiveness stress analysis model for simulation of centrifugal shaking table test

Table 5 – Parameter for simulation

Void ratio	e_0	1.00
Dilatancy parameter	λ	1.20
	μ	0.21
Internal frictional angle	ϕ_f	40°
Compression index	Cc	0.015
Poisson ratio	ν	0.33
Hardening parameter	k_s	0.0003
Coefficient of permeability	k	8.0×10^{-5}(m/s)



(a) Subsidence



(b) Inclination angle

Fig. 10 – Comparison between analytical and experimental values of house deformation

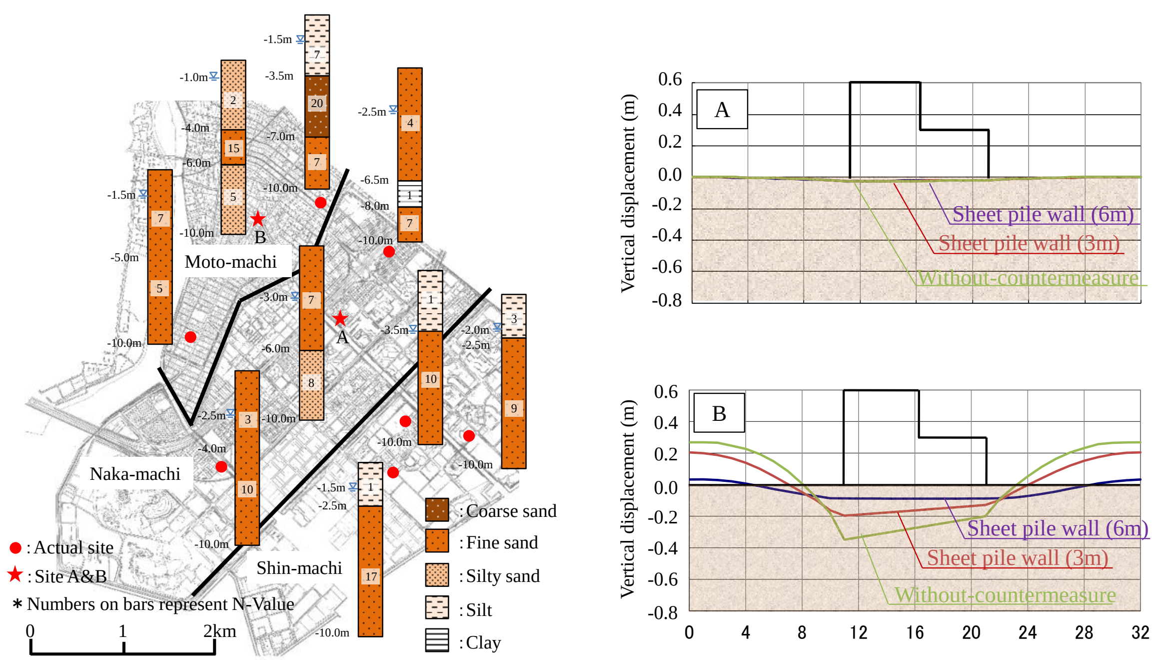
Fig. 10 shows the comparison of analytical results and centrifugal test results, in terms of house subsidence and inclination. It is found that test results were sufficiently simulated by O-EFECT. Regarding 300 cm/s^2 results, there is a little difference between experimental and analytical values. Because C2 (300 cm/s^2) test was conducted after C1 test, ground condition may be affected by C1 event.

4.2 Evaluation on Effectiveness of Sheet Pile Wall Method at Actual Grounds

Fig. 11a shows the site locations and ground conditions adopted for the analyses. The analytical parameters were set regarding N-values of actual grounds, in accordance with the method recommended in the Code for Japanese highway bridges [5]. Input acceleration motion used in the analyses was the same as used in centrifugal shaking tests. Ampritude of the motion was chosen as 150 cm/s^2. The effective stress analyses were conducted with three cases; house with non-countermeasure case, 3 m sheet pile wall case, and 6 m sheet pile wall case in each target ground. Ground surface profiles after shake obtained by typical analyses are illustrated in Fig. 11b. Site A and B are selected from Fig. 11a.

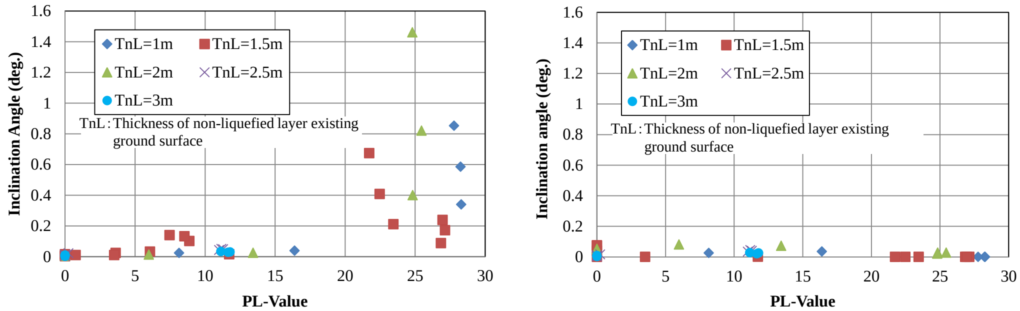
Regarding Fig. 11a, it is found that the water level of site A is deeper than that of site B. It means site A is less occurrence of soil liquefaction than site B. Therefore, in Fig. 11b, the vertical displacements of three cases were almost 0 m at site A. In contrast, the houses sunk down and leaned at the three cases in site B. The results of site B show that vertical displacements were reduced by sheet pile wall. As it was shown in experimental results, the longer sheet pile wall installed around house foundation, more effectiveness on house deformation appears.

Fig. 12 show relations between the inclination angle of the house and PL-value of the ground regarding house without-counterameasure case (Fig. 12a) and house with 6 m sheet pile wall case (Fig. 12b).



(a) Locations and boring data of actual sites (b) Ground surface profiles

Fig. 11 – Evaluation on effectiveness of sheet pile wall method at actual grounds



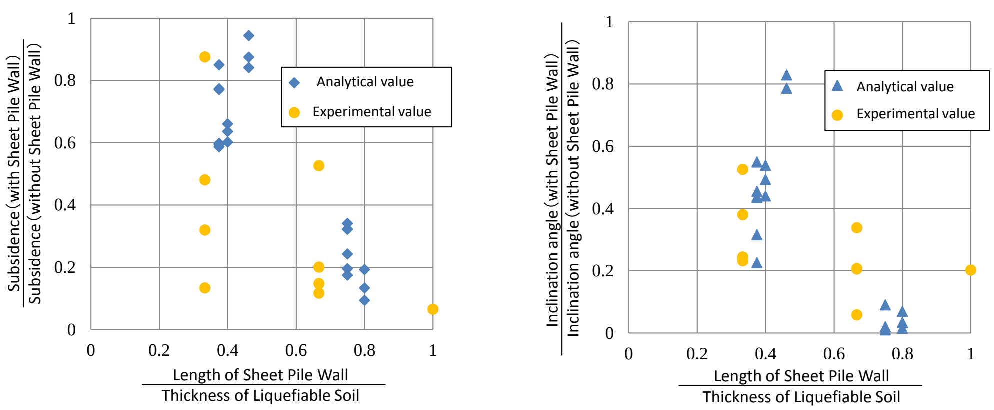
(a) House without-countermeasure (b) House with 6 m sheet pile wall

Fig. 12 – Comparison of house inclination angle between without-countermeasure and countermeasure

Relations between house inclination angles and PL-values are plotted on Fig. 12. These data are chosen at 50, 75, 100, 150, 200, 300 s, respectively after shake events start. Plots are categorized into five groups in terms of thickness of non-liquefied layer under the ground surface (TnL; hereafter). FL-values; necessary to calculate to PL-value, were identified from excess pore water pressure ratio computed by the analyses, in accordance with the method presented in code for the rail way structures [9]. In this method, however, when excess pore water pressure ratio becomes 1.0, FL-value can be identified between 0 and 0.5. Thus, in this study, in that case FL-value is chosen as 0.5.

Regarding without-countermeasure case (Fig. 12a), house inclination angle is large under the ground conditions of PL-value > 20 and TnL < 2 m. In contrast, with 6 m sheet pile wall house inclination angle is reduced to almost 0 degree under the same ground condition, as shown in Fig. 12b.

Analytical results (blue plots in figures) and experimental results (yellow plots in figures) are summarized in Fig. 13a and 13b. Data are selected from the ground condition of PL-values > 20. The horizontal axis and vertical axis are chosen as the same as shown in Fig. 8. The trende of analytical results are similar to experimental results. From this result ,it is found that the sheet pile wall method is efficient on reducing house deformation induced by soil liquefaction even in actual ground conditions.



(a) Subsidence (b) Inclination angle

Fig. 13 – Comparison between analytical and experimental values of house deformation

5. Conclusion

In this paper, the sheet pile wall method for countermeasure against house subsidence and inclination induced by soil liquefaction was proposed. Some gravitational and centrifugal tests were conducted in order to examine effectiveness of the sheet pile wall method. In addition, the effective stress analyses were also conducted under various ground condition to estimate effectiveness of the wall at actual ground. These results indicate as follows.

1) It is able to reduce the house subsidence and inclination by using the sheet pile wall, even if occurrence of liquefaction of house foundation ground is allowed.

2) Effectiveness of the sheet pile wall, in terms of house subsidence and inclination, is affected by the sheet pile length.

3) Effectiveness of the sheet pile wall, in terms of house inclination, is affected by the fixed condition. The sheet pile wall fixed with house foundation is more effective than that free from house foundation.

4) By comparing the results from centrifugal test and computer simulation, it is confirmed effectiveness of the sheet pile wall method can be estimated by the dynamic effective stress analysis.

5) According to analyses results, the sheet pile wall is more effective especially under the following conditions, i.e. A) thickness of surface non-liquefiable layer is less than 2.0 m, B) PL-value of target ground is exceeding 20, and C) the ratio of the length of the sheet pile wall to thickness of liquefiable soil is exceeding 0.5.

6. Acknowledgements

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