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Behavior of small building foundations with raft and box confinement during liquefaction by using cyclic simple shear test in 1-G

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Abstract

Liquefaction occurs due to a cyclic shear stress by earthquake and buildings are damaged such as settlement or inclination. The confining ground under the building is one of the methods for preventing liquefaction in the ground, because it can restrain the shear deformation. In this study, cyclic simple shear test was conducted in 1-G for proposing the countermeasure method using a raft foundation with casing. The dispersing time of excess pore water pressure is the most important in this experiment. To decide more suitable coefficient of permeability of the model ground for this experiment, falling head permeability test was performed to find the coefficient by changing some mixing ratio of water with Na-CMC or glycerin. After the permeability test, simple shear test was conducted with some models. There are the follow conclusions by the result of this study. (1) The raft foundation with casing can reduce settlement and inclination of building. (2) Peak value of excess pore water pressure can't be decreased in the casing. (3) The aqueous solution of Na-CMC is better to conduct simple shear test in 1-G for adjusting the time of dispersing excess pore water pressure than the aqueous solution of glycerin.

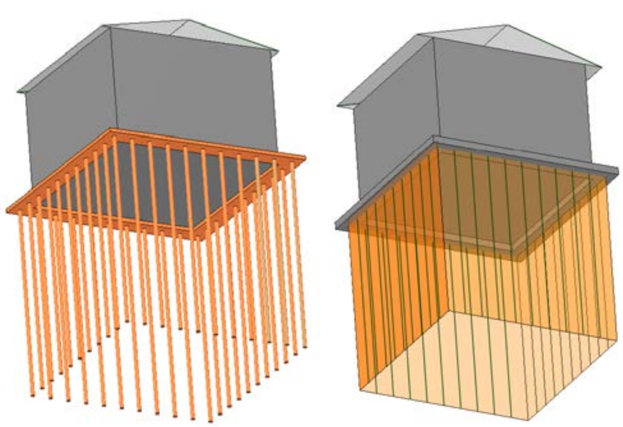
Keywords: Liquefaction, Countermeasure method, Small building, Raft foundation, Simple shear test

1. Introduction

Liquefaction occurs due to a cyclic shear stress by earthquake, and buildings are damaged such as settlement or inclination. During ground shaking by earthquake, pore water pressure is increased, and effective stress is decreased. Thus, the ground loses the shear strength and flows easily. In Japan, liquefaction brought about serious damage for residential housing area in 2011. The Tohoku-Pacific Ocean Earthquake (on March 11 2011.) was the greatest earthquake ever recorded in Japan. There are a lot of reclaimed ground which were build up with saturated sandy soil in Japan, so such ground liquefied easily by long period and long duration earthquake. Many reclaimed ground were damaged due to liquefaction even though the place was so far from the seismic center. However, the diffusion of the countermeasure method for residential housing is not enough in Japan. A simple and low cost countermeasure needs developing for not only Japan but also the countries in which many earthquakes happen. Confining ground under the building is one of the methods for preventing liquefaction, because it can restrain the shear deformation of the ground under the building.

In this study, proposed method is very simple way which is combination of raft foundation and casing pile. The casing means a structure which confines ground under the building with line of small piles, seat pile or underground wall. Fig.1 shows the image of this countermeasure methods. The head of small piles or seat pile are jointed to the concrete raft foundation. The desirable effects of this method is shown in Fig.2. One of the effects is increasing bearing capacity of the building foundation, and the other is restraining a shear deformation when the ground becomes weak. If liquefaction occurs, the soil under the building moves along the sliding surface. However, the casing can restrain this movement and the serious damage such as settlement or inclination can be decreased.

Cyclic simple shear tests were conducted in 1-G for proposing the countermeasure method using a raft foundation with casing in this paper. The models of several casing piles were made and their effects for liquefaction were compared with no countermeasure method. The underground wall as the countermeasure method against liquefaction has already been used in Japan for the foundation of high rise buildings and a lot of studies about its availability have been performed. However, the cost of underground wall such as made of concrete is very high, therefor it is inappropriate for the small buildings like residential housings. This research is intended to suggest inexpensive and effective method with low material costs and construction costs. If line of small piles with wide span can reduce the damage due to liquefaction, it needs not to perfectly enclose the ground of under the building such as underground wall or seat pile. The final objective of this study is to provide countermeasure method with higher cost-effectiveness by an efficient method, but the contents of this paper are basic research for the raft foundaion with caising pile. The contents of this paper are as follows. Firstly, on performing model experiment, the similarity rule is considered theoritically. Secondly, adjustment of scaling factors for 1/100 model is made based on the similarity rule. Finally, cyclic simple shear tests are conducted on some models of raft foundation with casing piles, and discussion is made to these results.



(a) Line of small piles (b) Seat pile

Fig. 1 – Image of raft foudation with casing

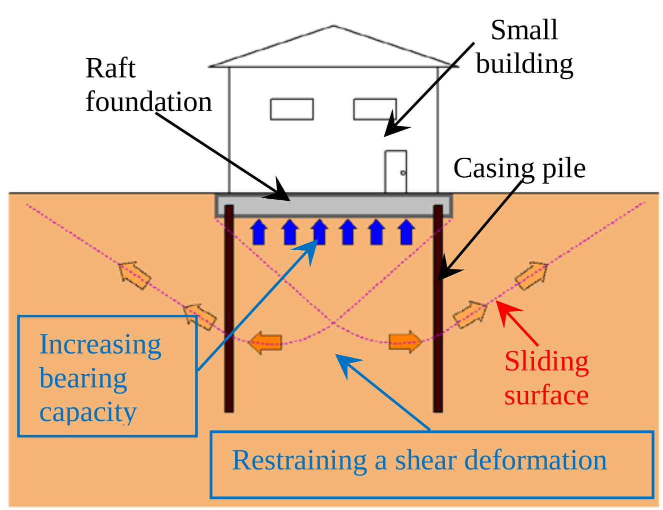


Fig. 2 – Desirable effects

2. Similarity rule

At first, similarity rule is considered from the basic equations which govern the equilibrium conditions. Unlike the centrifuge test which can make the same value of stress condition in prototype ground, the similarity rule should be considered to conduct experiment in 1-G. In this paper, the similarity rule which was shown by Iai (1988) [1] is applied. The derivation process is omitted due to limit of paper pages. The basic equations for saturated soil, structures and fluid are made for the prototype and the model. Each equation for the prototype and the model are compared and the equations are solved for three independent scaling factors. The geometric scaling factor λ, the scaling factor for density of saturated soil λ_ρ and the scaling factor for strain of saturated soil λ_ε are regarded as the independent scaling factors. Furthermore, in the special case in which λ_ρ=1 and $\lambda_\varepsilon = \lambda^{1/2}$, the conditions of similarity rule are reduced. In this case, the similarity rule for the soil skeleton becomes the same as that developed by Kagawa (1978) [2], and Kokusho and Iwatate (1979) [3]. Table 1 shows the similarity rule and the scaling factors are considered when experiment is performed. In which, the scale of experiment model in this study is 1/100, so geometrical scale λ is 100. In this similarity rule, scaling factors which are especially considered are time λ_t, permeability λ_k, flexural rigidity λ_{EI} and traction acting on the boundary $\lambda_{\bar{T}}$. The vibration frequency of cyclic shear test is decided considering time of the scaling factor λ_t. Permeability of the scaling factor λ_k is related to the dispersing time of excess pore water pressure, it is described more detail in the following chapter. Flexural rigidity of the scaling factor λ_{EI} is considered for making models of casing pile. When making a model of raft foundation, traction acting on the boundary $\lambda_{\bar{T}}$ is considered.

Table 1 – Similarity rule

Scaling factors	Similitude shown by Iai [1]	Special case in which λ_ρ=1 and λ_ε=$\lambda^{\frac{1}{2}}$	Similitude applied for this study $\lambda = 100$
λ_t(Time)	$(\lambda\lambda_\varepsilon)^{\frac{1}{2}}$	$\lambda^{\frac{3}{4}}$	31.6
λ_u(Displacement)	$\lambda\lambda_\varepsilon$	$\lambda^{\frac{3}{2}}$	1000
λ_σ(Total stress)	$\lambda\lambda_\rho$	λ	100
$\lambda_{\sigma'}$(Effective stress)	$\lambda\lambda_\rho$	λ	100
λ_p(Pore water pressure)	$\lambda\lambda_\rho$	λ	100
λ_D(Tangent modulus of soil)	$\lambda\lambda_\rho/\lambda_\varepsilon$	$\lambda^{\frac{1}{2}}$	10
λ_k(Permeability of soil)	$(\lambda\lambda_\varepsilon)^{\frac{1}{2}}/\lambda_\rho$	$\lambda^{\frac{3}{4}}$	31.6
λ_{EI}(Flexural rigidity)	$\lambda^4\lambda_\rho/\lambda_\varepsilon$	$\lambda^{\frac{7}{2}}$	10^7
λ_{ρ_f}(Density of pore water)	λ_ρ	1	1
λ_{ρ_b}(Density of the structure)	$\lambda\lambda_\rho$	λ	100
$\lambda_{\bar{T}}$(Traction acting on the boundary)	$\lambda\lambda_\rho$	λ	100
$\lambda_{\bar{u}}$(Displacement on the boundary)	$\lambda\lambda_\varepsilon$	$\lambda^{\frac{3}{2}}$	1000
$\lambda_{\bar{p}}$(Water pressure on the boundary)	$\lambda\lambda_\rho$	λ	100

3. Falling head permeability test

The dispersing time of excess pore water pressure is the most important in this experiment, therefor the coefficient of permeability of model sand (Toyoura sand) should be adjusted. Two type viscous fluids are prepared to decide more suitable for this experiment. One is aqueous solution of Na-CMC and the other is the aqueous solution of glycerin. Na-CMC is often used for thickening agent and it is known as harmless to environment. Glycerin is often used for research on liquefaction to consider the similitude of coefficient of permeability [4]. According to the similitude, appropriate coefficient of permeability is determined, and falling head permeability test is performed to find the coefficient by changing some liquid density of Na-CMC and glycerin. Falling head permeability test is often used for the measurement of soil with low coefficient of permeability. Toyoura sand has high permeability in case of water, but viscous fluids can decrease the permeability of Toyoura sand. When falling head permeability test is conducted, the coefficient of permeability "k" can be calculated by the equation (1). Fig.3 shows illustration of falling head permeability test. Incremental time which is t_1 to t_2 dropping water in the stand pipe is measured from height h_1 to h_2.

$$k = \frac{La}{A(t_2-t_1)}\log_e\frac{h_1}{h_2} \fallingdotseq \frac{2.303La}{A(t_2-t_1)}\log_{10}\frac{h_1}{h_2} \qquad (1)$$

where,

L: Height of the soil specimen

A: Cross sectional area of the specimen

a: Cross sectional area of the stand pipe

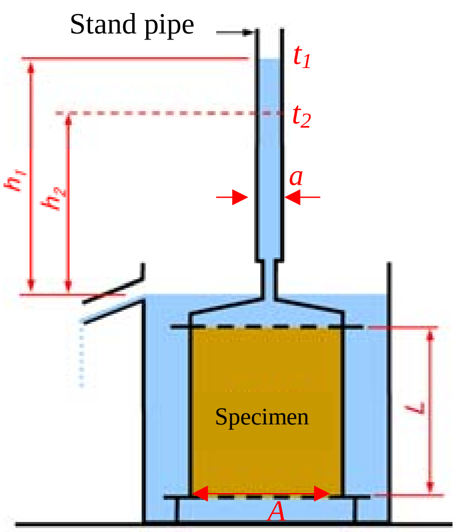


Fig. 3 – falling head permeability test

The results of falling head permeability tests are shown in Table 2 and 3. The coefficient in case of Na-CMC is the average value of three times to confirm repeatability. Na-CMC is powdered in the solid state and it is easy to control the liquid density. Permeability test in case of normal water is performed to compare with viscous fluids, and its coefficient of permeability is 2.61×10^{-2} cm/s. This permeability is equal to the permeability of prototype ground. The permeability in case of Na-CMC or glycerin is equal to the permeability of model ground, therefor the coefficient of permeability ratio λ_k can be calculated by the equation (2). The relationship between the liquid density and coefficient ratio are shown in Fig.4 and Fig.5. The similitude demands $\lambda_k = 31.6$ in this study, therefor 0.85% Na-CMC and 83% glycerin are suitable as shown in Fig.4 and Fig.5.

Table 2 – Coefficient of permeability (aqueous solution of Na-CMC)

		Liquid density of Na-CMC (%)				
		0.5	0.7	0.8	0.9	1.0
Permeability (cm/s)	first	2.69×10^{-3}	1.40×10^{-3}	0.95×10^{-3}	6.59×10^{-4}	5.49×10^{-4}
	second	3.33×10^{-3}	1.41×10^{-3}	1.04×10^{-3}	6.99×10^{-4}	5.79×10^{-4}
	third	2.86×10^{-3}	1.60×10^{-3}	0.89×10^{-3}	7.51×10^{-4}	4.88×10^{-4}
	average	2.96×10^{-3}	1.47×10^{-3}	0.96×10^{-3}	7.03×10^{-4}	5.39×10^{-4}

Table 3 – Coefficient of permeability (aqueous solution of Glycerin)

	Liquid density of glycerin (%)				
	79.0	81.4	82.6	83.0	83.4
Permeability (cm/s)	1.59×10^{-3}	1.30×10^{-3}	1.11×10^{-3}	7.53×10^{-4}	6.90×10^{-4}

$$\lambda_k = \frac{\text{Coefficient of permeability in case of prototype ground}}{\text{Coefficient of permeability in case of of model ground}} = \frac{\text{Coefficient of permeability in case of normal water}}{\text{Coefficient of permeability in case of viscous fluid}} \tag{2}$$

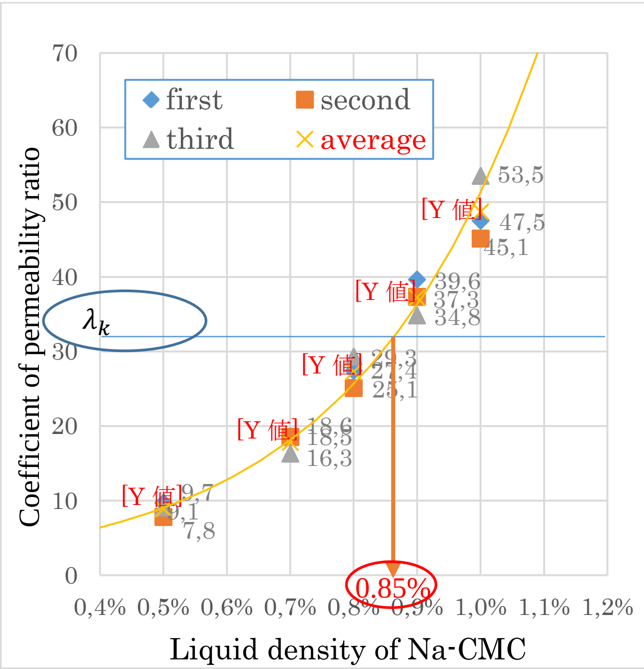


Fig. 4 – Relationship between Liquid density of Na-CMC and coefficient of permeability ratio

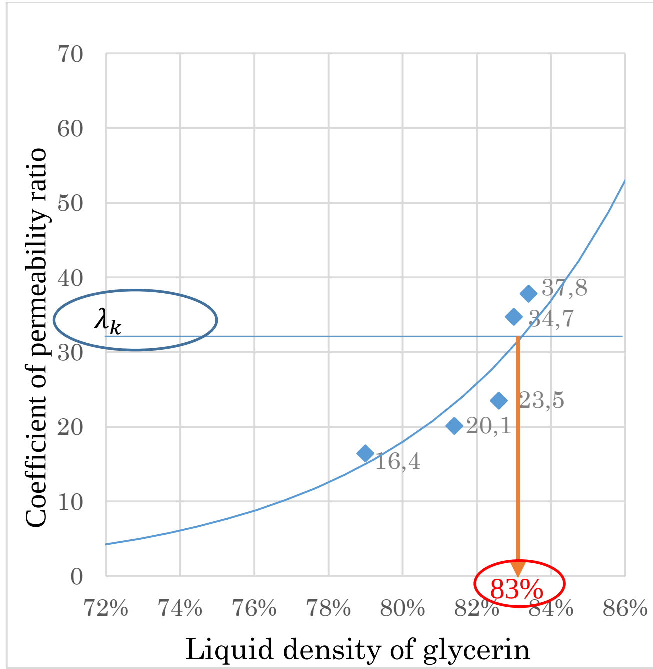
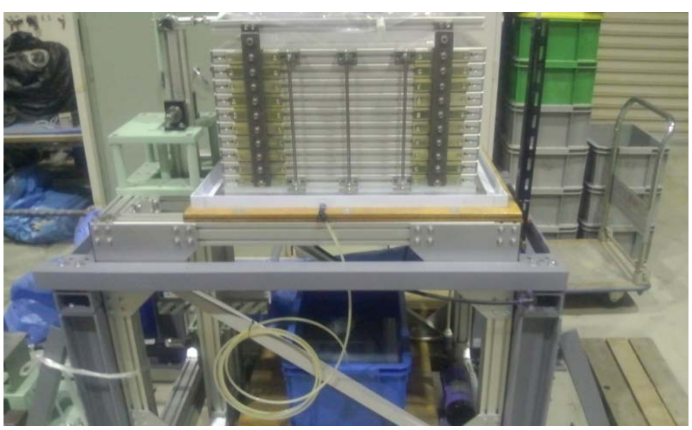


Fig. 5 – Relationship between Liquid density of glycerin and coefficient of permeability ratio

4. Cyclic simple shear test

4.1 Cyclic simple shear test equipment

In this study, cyclic simple shear test equipment is used for the liquefaction test as shown Fig.6 and Fig.7. Liquefaction is closely related to the shear deformation of ground. The soil box of simple shear test equipment consists of ten frame layer, therefor it can give simple shear to the model ground. Saturated ground is prepared with relative density: Dr=50%. Shear strain amplitude is set as 4% and it is applied sine wave with 3Hz frequency.



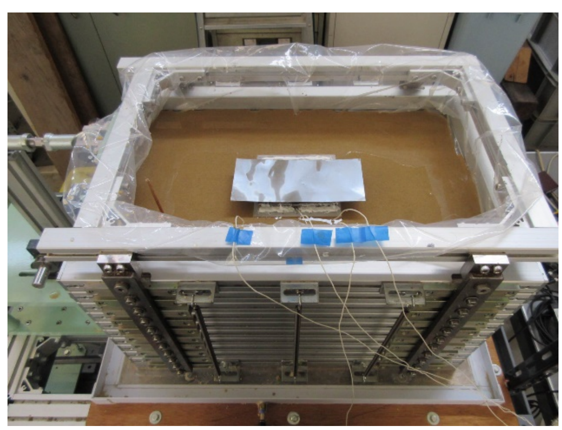


Fig. 6 – Cyclic simple shear test equipment

Fig. 7 – Model ground

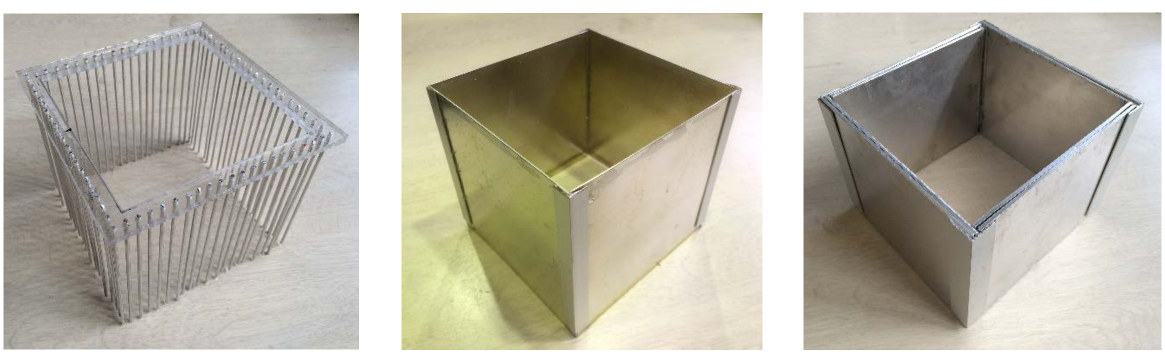
The models of raft foundation and casing pile are made of aluminum material. The ground contact pressure of prototype and model structure are shown in Table 4. The prototype of small house is assumed with 1.4tf/m^2 ground contact pressure. The size of prototype raft foundation is 10m×10m. The ground contact pressure of model raft foundation is set to 0.014tf/m^2, because similitude of traction acting on the boundary $\lambda_{\bar{T}}$ is demanded as 100. Therefore, the weight of model raft foundation is 140g and the size is 100mm×100mm. However, the model is only raft foundation because behavior of inclination is complicated when superstructure of building is simulated. Table 5 shows flexural rigidities of prototype and model of casing pile. Similitude of flexural rigidity λ_{EI} is considered when the casing pile models is made. As materials of prototype casing pile, seat pile is steel, small piles are timbers and underground wall is concrete. The models are made and those ratio of flexural rigidity becomes approximately 10^7. The pictures of casing pile models are shown in Fig.8.

Table 4 – Ground contact pressure of prototype and model structure

	Prototype (Small house)	Model (Raft foundation)	Similitude of traction acting on the boundary $\lambda_{\bar{T}}$
Ground contact pressure	1.4tf/m^2	0.014tf/m^2	100

Table 5 – Flexural rigidity of prototype and model structure

	Specification / Prototype EI_p(N/cm^2)	Specification / Model EI_m(N/cm^2)	Ratio of flexural rigidity EI_p/EI_m	Similitude of flexural rigidity λ_{EI}
Seat pile	Steel seat pile	Aluminum seat Thickness : 0.8mm	2.8×10^7	10^7
	8.2×10^{10}	2.9×10^3		
Small piles	Timber pile Diameter : 200mm	Aluminum rod Diameter : 2mm	1.2×10^7	
	6.3×10^9	5.3×10^2		
Underground wall	Concrete Thickness : 200mm	Aluminum seat Thickness : 4mm	0.4×10^7	
	1.3×10^{12}	3.6×10^5		

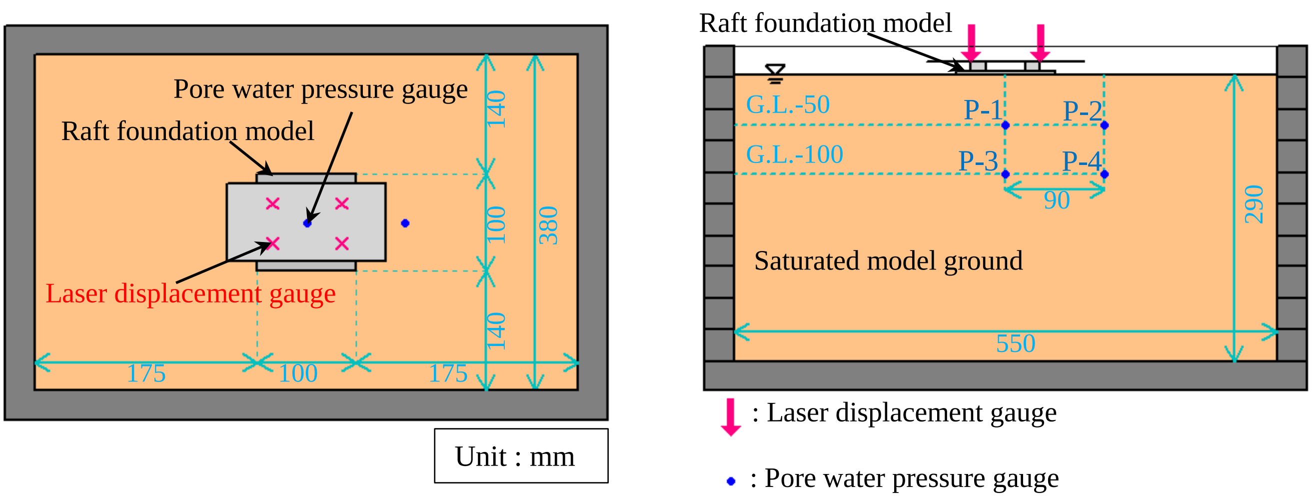


(a) Small piles (b) Seat pile (c) Underground wall

Fig. 8 – Casing pile model structures

4.2 Preliminary experiment

Before main comparative experiments with models of countermeasure method, preliminary experiments were conducted using normal water, Na-CMC and glycerin liquid solution for pore liquid in the model ground. Preliminary experiment was performed with only raft foundation model. The model ground is shown in Fig.9. Fig.10 shows the measured result of excess pore water pressure. The vertical axis is excess pore water ratio, which is the value of measured pore water pressure divided by initial effective stress. Therefore, complete liquefaction occurs when the peak value reaches at 1. The complete liquefaction occurs in each case, because the peak value exists around 1. The excess pore water pressure disperses immediately after shaking, when the normal water is used. The normal water is not suitable for this experiment, because the excess pore water pressure does not disperse immediately in the real liquefaction phenomenon. The pore water pressure does not disperse maintaining the peak value, when the aqueous solution of glycerin (liquid density: 83%) is used. This is caused by the fact that viscosity of glycerin becomes too strong. This also differ from the real liquefaction, therefore, aqueous solution of glycerin is not suitable for the 1/100 sized model experiment. In contrast, the behavior of excess pore water pressure is similar to the real liquefaction phenomenon, when the aqueous solution of Na-CMC (liquid density: 0.85%) is used. The aqueous solution of Na-CMC is better to conduct in this experiment for adjusting the time of dispersing excess pore water pressure than the aqueous solution of glycerin.



(a) Plane view (b) Cross sectional view

Fig. 9 – Model ground of preliminary experiment

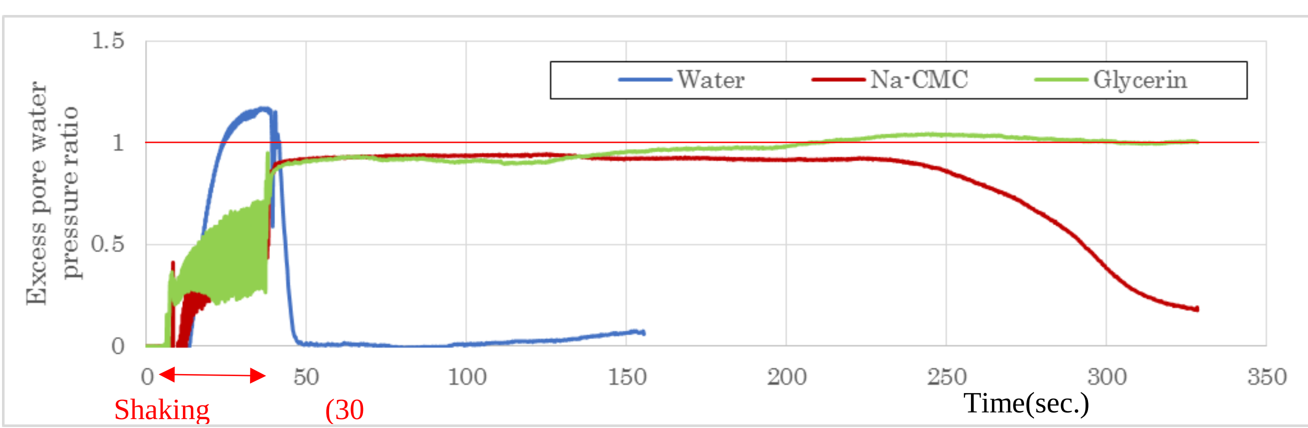


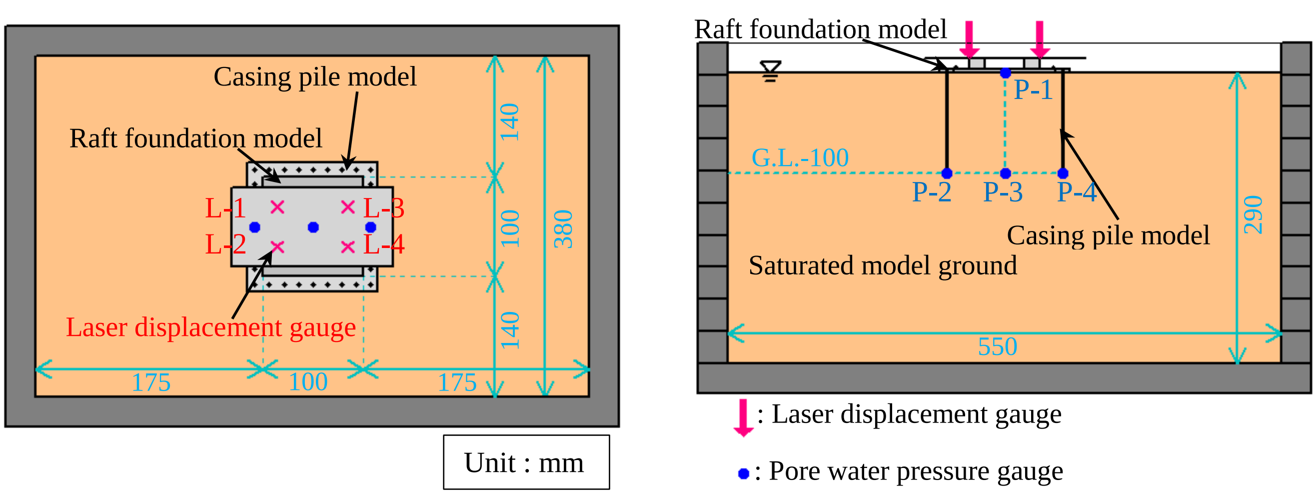
Fig. 10 – The measured result of excess pore water pressure at P-1 in the Fig.9

4.3 Cases of cyclic simple shear test

The test cases are shown in Table 6. Fig.11 shows model ground with casing pile model. Case-1 is only raft foundation model without countermeasure, as shown in Fig.9. Case-2 to 4 are seat pile cases which are different in depth of penetration (100mm or 50mm) with fixed or unfixed. “Fixed or unfixed” means the joint conditions of raft foundation and head of casing pile. Raft foundation and casing pile can move free relatively in case of unfixed condition. Case-5 to 15 are raft foundation with line of small piles cases. These cases have different depth of penetration and different pile intervals. The diameter of small pile model (D) is 2mm, and pile intervals (d) are set as 6, 10, 20, 60 and 120mm. Case-16 to 18 are underground wall models with different depth of penetration.

Table 6 – Experiment cases

Experiment cases	Countermeasure method			Depth of penetration	Weight of raft foundation	Weight of casing
Case-1	Only raft foundation			-	140g	-
Case-2	Seat pile (Thickness:0.8mm)		unfixed	100mm		105g
Case-3			fixed			
Case-4			fixed	50mm		52g
Case-5	Small piles (D=2mm)	Pile interval d=3D	unfixed	100mm		95g
Case-6			fixed			
Case-7			fixed	50mm		64g
Case-8		d=5D	fixed	100mm		60g
Case-9				50mm		45g
Case-10		d=10D	fixed	100mm		48g
Case-11				50mm		37g
Case-12		d=30D	fixed	100mm		34g
Case-13				50mm		30g
Case-14		d=60D	fixed	100mm		31g
Case-15				50mm		28g
Case-16	Underground wall (Thickness:4.0mm)		unfixed	100mm		580g
Case-17			fixed			
Case-18			fixed	50mm		264g



(a) Plane view (b) Cross sectional view

Fig. 11 – Model ground with casing pile model

4.4 Results of cyclic simple shear test

The pore water pressures are shown in Fig.12 and Fig.13. Seat pile model is Case-3, Small piles model is Case-8 and Underground wall model is Case-17. As shown Fig.12, the pore water pressure at P-3(in Fig.11) is inside of casing. The peak value of excess pore water pressure ratio exceeds 1, therefore complete liquefaction occurs in each case. As shown Fig.13, the pore water pressure at P-2 (in Fig.11) is edge of casing pile. The peak value of excess pore water pressure ratio also exceeds 1, therefore complete liquefaction occurs in each case. At the other measuring points P-1 and P-4(in Fig.11), the peak value of excess pore water pressure ratio also exceeds 1. These results shows that the casing piles can't prevent completely the increase of excess pore water pressure.

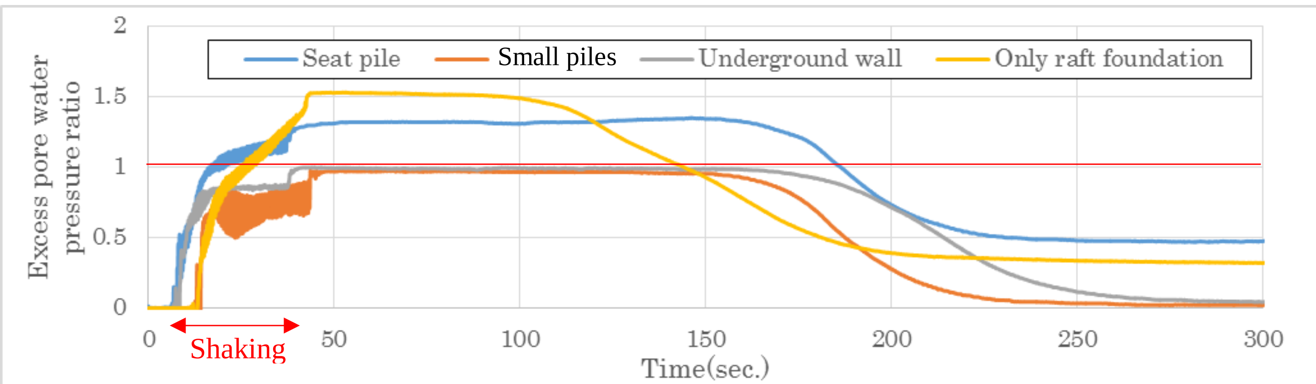


Fig. 12 – Measured results of pore water pressure at P-3 in the Fig.11

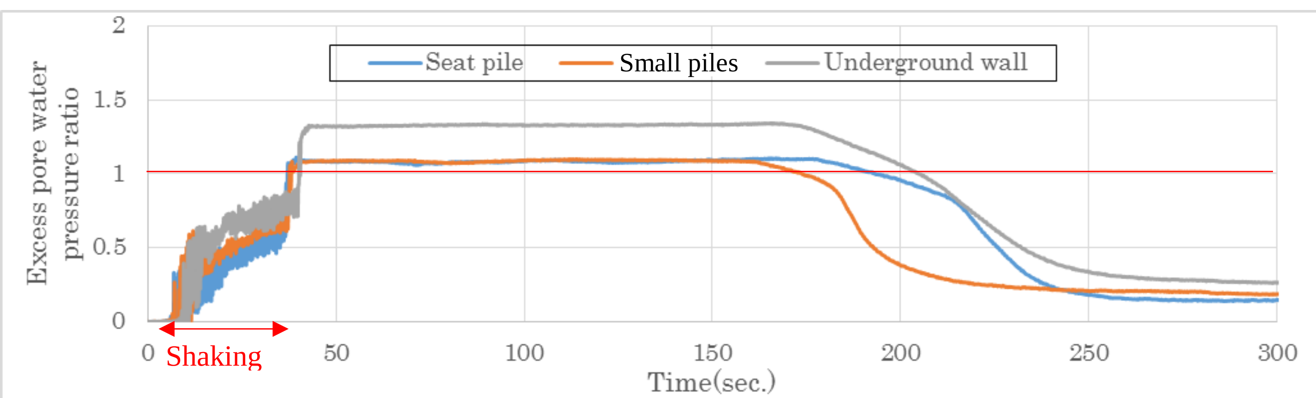


Fig. 13 – Measured results of pore water pressure at P-2 in the Fig.11

The measured results of settlement including four examples (Case-1, 3, 8, 17) are shown in Fig.14. These lines represent time history of settlement at center of raft foundation because the measured results are average of four laser displacement gages. Settlements increases rapidly during shaking, and it increases slowly after shaking. It can be seen that the increase of settlements were stopped around the same time when the excess pore water pressure almost completely disperses. The displacements are regarded as the final settlement δ_{fin} around 300 seconds. The settlement of in case underground wall is larger than that of seat pile and small piles, because the weight of the underground wall model is largest. The influence of the differences of model weight for settlements needs to be considered and corrected. Therefore, an index δ_{fin}/W is adopted for comparing each other's without difference of weight. The weight W is total weight of the model raft foundation and casing pile.

Table 7 shows weight of model W, final settlement δ_{fin} and index δ_{fin}/W of each case. This index indicates higher effect of reducing settlement when the index value is smaller. Of course, the index of only raft foundation (Case-1) is the largest in all case. Indexes of Case-2 and Case-5 with unfixed condition are larger than the others cases. This result indicates that fixed condition has more effectiveness than unfixed condition. Dividing into kind of the models, the indexes of seat pile and small piles are 30-50% and index of underground wall is 20% compared with it of only raft foundation.

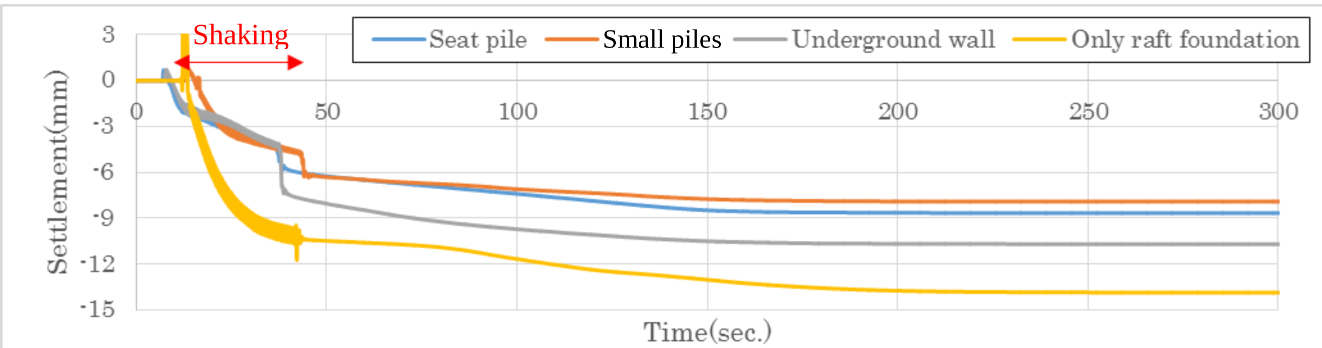


Fig. 14 – Measured results of settlement of raft foundation

Table 7 – Experiment cases

Experiment cases	Countermeasure method			Depth of penetration (mm)	Weight of model W(g)	Final settlement δ_{fin} (mm)	δ_{fin}/W
Case-1	Only raft foundation			-	140	14.0	0.1
Case-2	Seat pile (Thickness:0.8mm)		unfixed	100	245	11.2	0.045
Case-3			fixed			8.2	0.033
Case-4			fixed	50	192	4.1	0.021
Case-5	Small piles (D=2mm)	d=3D	unfixed	100	235	12.5	0.053
Case-6			fixed			7.6	0.032
Case-7			fixed	50	204	6.7	0.032
Case-8		d=5D	fixed	100	200	7.9	0.040
Case-9				50	185	9.5	0.051
Case-10		d=10D	fixed	100	188	2.8	0.015
Case-11				50	177	7.2	0.041
Case-12		d=30D	fixed	100	174	5.2	0.029
Case-13				50	170	7.1	0.042
Case-14		d=60D	fixed	100	171	6.1	0.037
Case-15				50	168	6.5	0.039
Case-16	Underground wall		unfixed	100	720	12.5	0.017

Case-17	(Thickness:4.0mm)	fixed			10.7	0.015
Case-18		fixed	50	404	9.9	0.025

4.5 Discussion on pile spacing

The underground wall has high effectiveness of reducing settlement due to liquefaction. However, underground wall is not appropriate for the small building considering cost effectiveness. The effects of reducing settlement are little small compared with underground wall, but seat pile or small piles with enough effectiveness against liquefaction are easy to apply for residential housing. The indexes of small piles are almost the same as them of seat pile. This result shows that the raft foundation with small piles is more effective for cost and construction process than that of seat pile, because small piles can be spaced apart from each other and the cost of material and construction can be reduced. In other words, it is not necessary to enclose completely the ground under the building such as seat pile. Therefore, authors are focused on the difference of pile spacing and the experimental results are arranged about pile spacing. Fig.15 shows the relationships between the reducing ratio of settlement and the pile spacing. The horizontal axis is spacing ratio of piles which is defined as the ratio spacing of piles (d) / diameter of pile (D). The results of seat pile and underground wall are shown together as the case with spacing is 0 in the figure to compare with small piles. The vertical axis is the ratio which is defined by equation (3). This ratio shows the reducing effects of settlement by the small piles, seat pile and underground wall. As shown Fig.15, the effects of reducing settlement are almost same with the difference of pile spacing. In most cases, the settlements in case of countermeasures are less than half of the settlement in case of only raft foundation. This means that the raft foundation with small piles is the effective countermeasure method. Based on the measured results of settlement, the inclinations of raft foundation are calculated supplementarily. The reducing ratio of inclination is defined as same of the reducing ratio of settlement. As shown Fig.16, however these values are in an unbound state, the inclination is reduced in many cases. Thus, the result of cyclic simple shear test shows the possibility that the raft foundation with paled casing of small piles can reduce settlement and inclination of building. Though, an appropriate spacing of piles is not able to be proposed from these results, therefore a further study with more rigorous is necessary.

$$\text{Reducing ratio of settlement} = \frac{\text{Index of Small piles, Seat pile, Uuderground wall } \delta_{fin}/\mathrm{W}}{\text{Index of only raft foundation } \delta_{fin0}/\mathrm{W}_0} \tag{3}$$

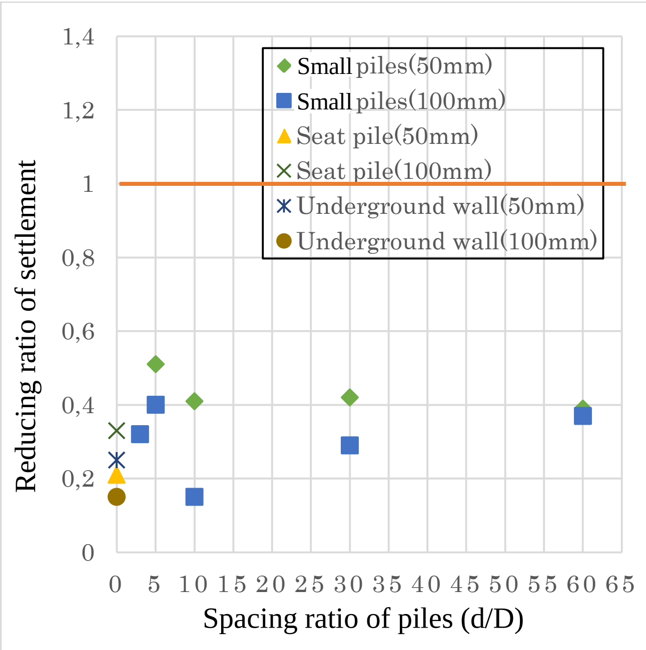


Fig. 15 – Relationships between reducing settlement and Spacing ratio

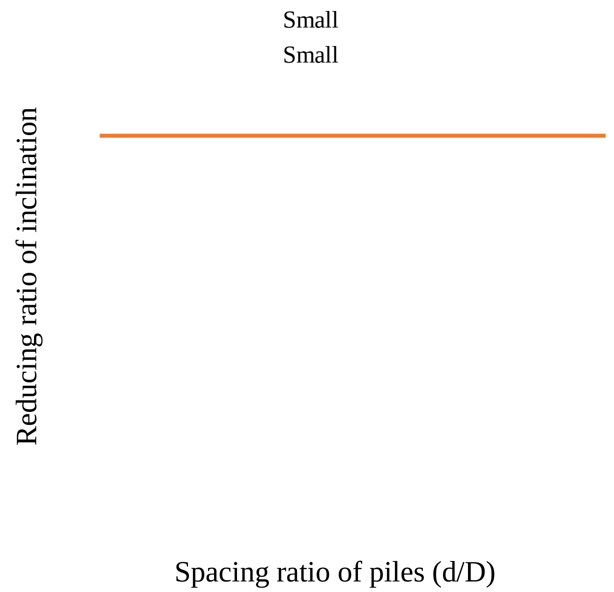
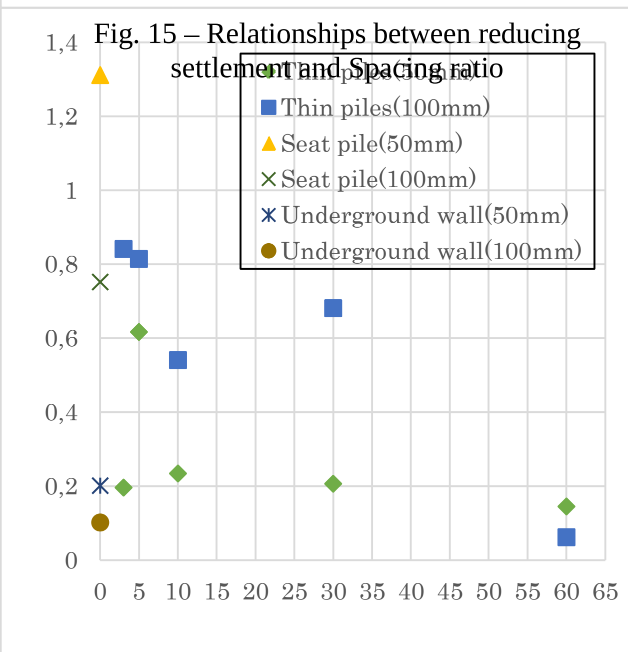


Fig. 16 – Relationships between reducing inclination and Spacing ratio



5. Conclusion

In this study, there are the following conclusions. (1) The raft foundation with casing can reduce settlement and inclination of building. Especially, the paled casing of small piles can reduce the settlement and inclination in the same as seat pile type or underground wall type. (2) The effect of the fixed model is higher than that of the unfixed model and, thus, the head of casing piles should be fixed to the raft foundation. (3) Peak value of excess pore water pressure can't be decreased by the casing. (4) The aqueous solution of Na-CMC is better to conduct simple shear test in 1g gravitation for adjusting the time of dispersing excess pore water pressure than that of the aqueous solution of glycerin. However, the all scaling factors of similarity are not able to be considered in this study. The further study with liquefaction analysis is necessary to confirm that raft foundation with paled casing of small piles is able to reduce the damage due to the liquefaction, and to develop the more practical method.

6. References

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