EXPERIMENTAL STUDY ON SEISMIC RESPONSE AND DYNAMIC ASEISMIC DESIGN OF BOX FOUNDATION COMPOSED OF UNITING CONTINUOUS UNDERGROUND WALLS

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ABSTRACT :

The box foundation composed of the uniting outer continuous underground wall, internal piles or lattice continuous underground wall has excellent earthquake resistance from the viewpoint of stability. Because the behavior during earthquake of the box foundation is complicated, the characteristic has not been clarified enough. Moreover, the evaluation method has not been necessarily established. In this study, the characteristics of this foundation during an earthquake are clarified by the verification experiments. Moreover, this paper proposes a practical and reasonable dynamic aseismic design method. It is based on the lumped mass model. It models friction springs and passive resistance springs between the soil and foundation reasonably. The results of simulation analyses, it is confirmed that the proposal method provides a more efficient aseismic design.

KEYWORDS: Continuous underground wall, Earthquake response, Frictional resistance, Strong earthquake motion, Vibration test, Dynamic analysis

1. INTRODUCTION

The foundation composed of uniting continuous underground walls and piles (the box foundation) is excellent in stability. The behavior of the box foundation is not clarified enough. Also the evaluation method of the box foundation is not established enough. Nakagawa et al studied the box foundation behavior of during earthquake. Wakamatsu et al performed the experimental studies on the box foundation behavior of during earthquake. Cyatani et al studied soil springs of the box foundation. Takahashi and Hayashi applied three dimensional finite element methods for analyses. Yamada and Miura also applied. According to such a background, in this study, the characteristics of the box foundation during an earthquake are clarified by the verification experiments. The experiment is the centrifuge test. And furthermore, this paper proposes a practical and reasonable dynamic aseismic design method. This method is based on the lumped mass model, and models friction springs and passive resistance springs between the soil and foundation. The results of the simulation analyses show the proposal method provides a more reasonable aseismic design.

2. EXPERIMENT METHOD

2.1. Outline of Experiments

When experimenting of the box foundation (Figure 1), the following points were noted. 1) The method by which the whole of the box foundation and soil can be modeled is used. 2) The method of appropriately evaluating the overburden pressure is used. 3) The method of appropriately evaluating the large deformation of soil is used. According to the above-mentioned, the centrifuge large shear box shaking table test was adopted as an experiment method. Also the experiments of pile foundation were performed for the comparison.

2.2. Experiment Method

The centrifuge gravitational force field is 50G. The excitation of box foundation and pile foundation about sine waves and large earthquakes were performed. The measurement was performed about shear force, horizontal subgrade reaction and friction force of the continuous underground wall, pile strain, building and soil acceleration, etc.

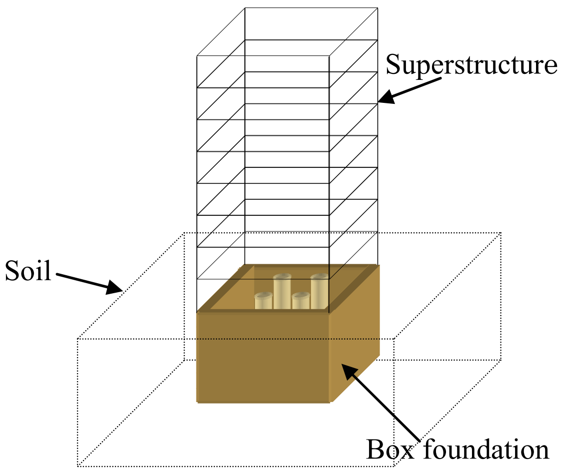
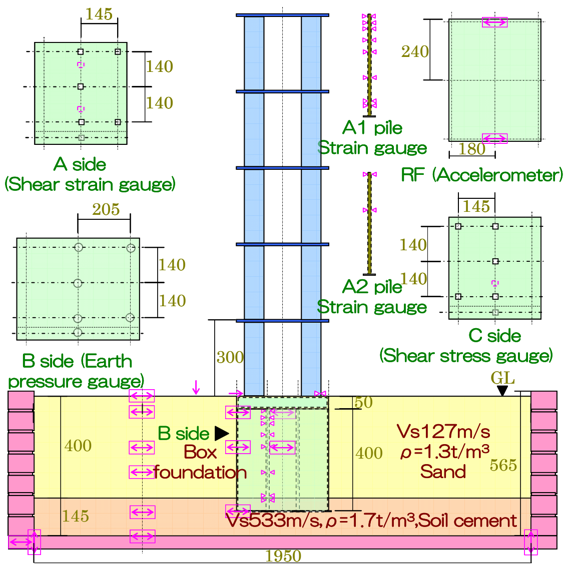
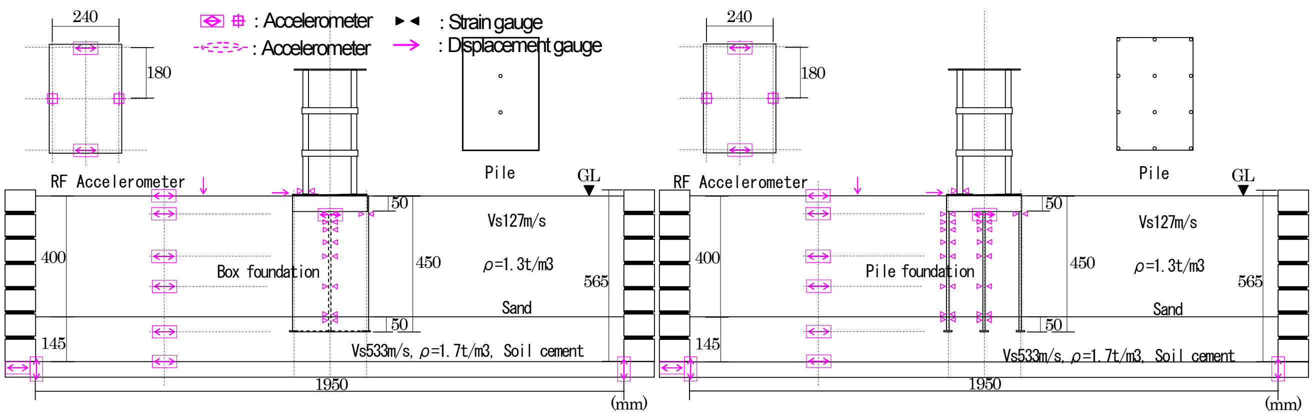


Figure 1 Box foundation



(a) A model



(b) B model (c) C model

Figure 2 Outline of test model

2.3. Outline of Test Model

The outline of test models is shown in Figure 2. The A model modeled a high rise building, a box foundation, soil, and bearing stratum. The box foundation length is 20m. The box foundation end is embedded to bearing stratum. The height of the building is 75m. The ground plane is 40×100m, and the depth is 27.5m. 2×3 piles are set up in the continuous underground walls. The frequency of the building is 0.57Hz. The B model modeled a general building, a box foundation, soil, and bearing stratum. The box foundation length is 20m. The height of the building is 21m. 2 piles were set up in the continuous underground walls. The frequency of the building is 1.52Hz. The C model is a pile foundation (3×4 piles) though it is the same building as the B model. The soil property is shown in Table 1. In addition, the scale is described by 1G gravitational force field in consideration of the law of similitude (length, displacement: 50 times, velocity: 1 time, acceleration: 1/50, time, period: 50 times, frequency: 1/50). The following is similarly described by the converted scale.

2.4. Input Motion

The excitation of sine waves and large earthquakes are performed. The input motion of the large earthquake excitation is the simulated earthquake ground motion specified by the Japanese Building Standard Law. The profile of the input motion is shown in Table 2.

Table 1 soil property

Depth（m）	Density（ton/m^3）	S,P wave velocity （m/s）	
		V s	Vp
0.00～1.25	1.30	64	127
1.25～2.50	1.30	84	167
2.50～3.00	1.30	92	184
3.00～4.25	1.30	99	197
4.25～5.50	1.30	106	212
5.50～6.50	1.30	112	224
6.50～7.75	1.30	117	233
7.75～8.75	1.30	121	242
8.75～10.00	1.30	125	250
10.00～12.50	1.30	131	262
12.50～15.00	1.30	138	275
15.00～17.25	1.30	143	286
17.25～19.50	1.30	148	296
19.50～20.00	1.30	151	301
20.00～27.25	1.67	533	843

Table 2 Input motion

	Level
Small earthquake	Safety limit earthquake×(1/20)
Medium earthquake	Safety limit earthquake×(1/10)
Damage limit earthquake	Safety limit earthquake×(1/5)
Safety limit earthquake	By Japanese building standard law
Great earthquake	Safety limit earthquake×1.5

Table 3 The maximum acceleration

	The maximum acceleration (cm/s^2)		
	Damage limit earthquake	Safety limit earthquake	Great earthquake
Superstructure	187	742	961
Foundation	69	412	589
Ground surface	166	914	1618

Table 4 The maximum shear force of continuous underground wall

Shear force of continuous underground wall (kN)		
Damage limit earthquake	Safety limit earthquake	Great earthquake
9538	41784	55599

Table 5 Comparison of the maximum acceleration ratio

Foundation/Ground surface		Damage limit earthquake	Safety limit earthquake	Great earthquake
The maximum acceleration ratio	Box foundation	0.79	0.75	0.68
	Pile foundation	1.20	0.97	1.02
The maximum acceleration (cm/s^2)	Box foundation	113/143	373/495	451/664
	Pile foundation	128/107	380/392	562/552

3. RESULTS OF EXPERIMENTS

3.1. Excitation of Sine Wave

The results of the A model without a superstructure is described. The sine wave is the natural frequency of soil. The relation between the friction force and the horizontal subgrade reaction of the continuous underground wall is shown in Figure 3. These ratios are about 0.7. The friction force and the horizontal subgrade reaction are measured with shear stress meters and soil pressure gauges. The relation between the horizontal subgrade reaction and the relative displacement, and the relation between the friction force and the relative displacement are shown in Figure 4. The friction force and the horizontal subgrade reaction have reached the ceiling. The displacement distribution of the free field and the continuous underground wall are shown in Figure 5. The comparison between the acceleration of internal soil and that of external soil is shown in Figure 6. The internal soil acceleration of the continuous underground wall is smaller than the external soil acceleration of that.

3.2. Results of Earthquake Excitation

The comparison of the maximum acceleration is shown in Table 3. The maximum acceleration on the foundation is about a half of that on the free field. The comparison of the response spectra is shown in Figure 7. The response of the box foundation is smaller than that of the free field. The maximum shear force of the continuous underground wall is shown in Table 4. The shear force is measured with three axes stress gauges. The maximum acceleration at the great earthquake is 1.8 times that at the safe limit earthquake, on the other hand the maximum shear force of the continuous underground wall at the great earthquake is 1.3 times that at the safe limit earthquake.

3.3. Comparison between Box Foundation and Pile Foundation

The comparison of the maximum acceleration ratio (foundation / free field) is shown in Table 5. The maximum acceleration of the pile foundation and that of the free field are almost the same. However, the maximum acceleration of the box foundation is about 30 percent smaller than that of the free field. The comparison of the response spectra is shown in Figure 8. The response of the box foundation is smaller than that of the pile foundation. The input loss effect of the box foundation is larger than that of the pile foundation.

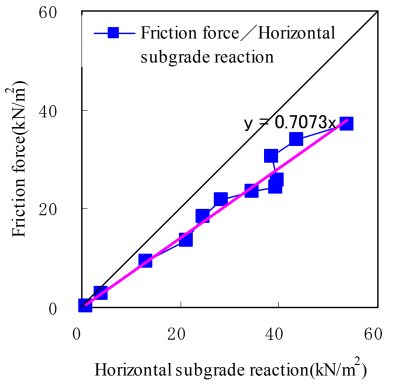
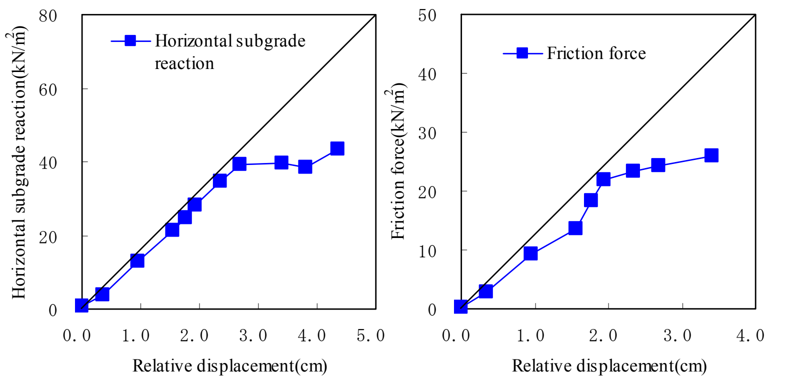


Figure 3 Relation between friction force and horizontal subgrade reaction of continuous underground wall



(a) Horizontal subgrade reaction (b) Friction force

Figure 4 Relation between horizontal subgrade reaction and relative displacement, and that between friction force and relative displacement

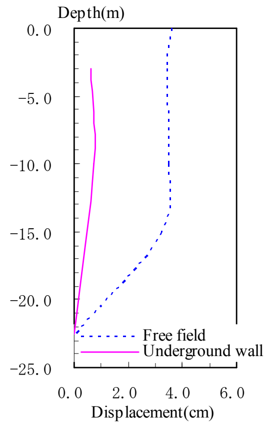


Figure 5 Displacement distribution of free field and continuous underground wall

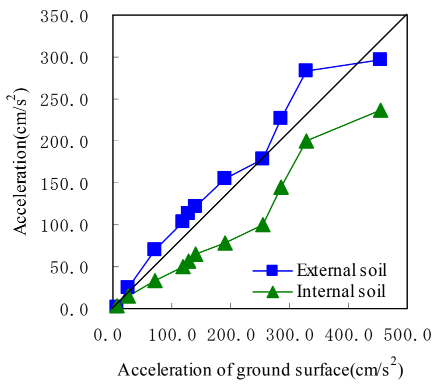
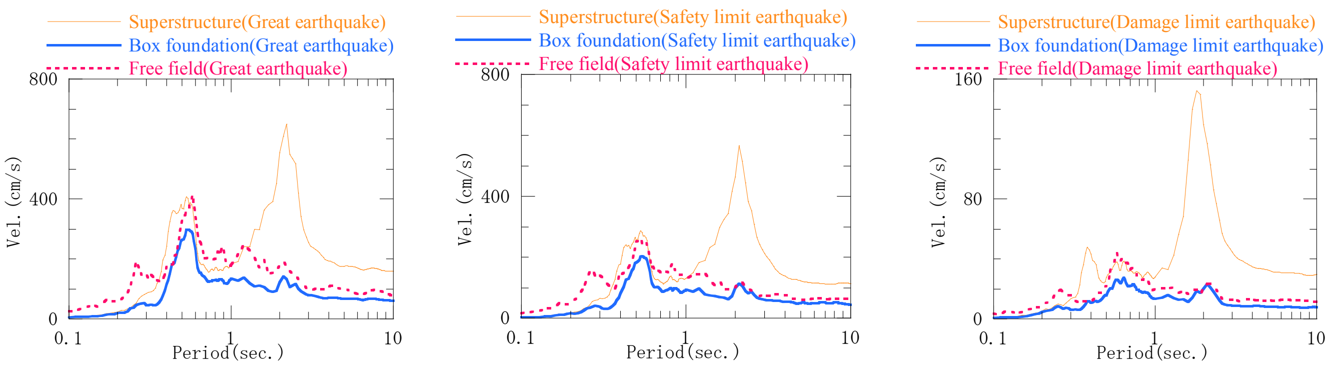
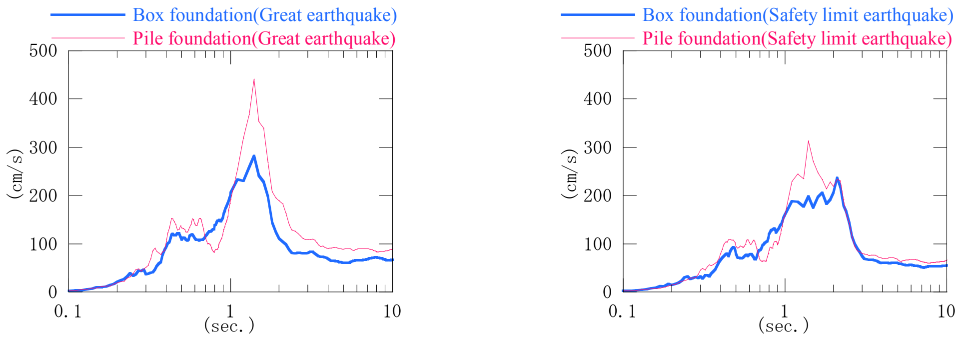


Figure 6 Comparison between acceleration of internal soil and that of external soil



(a) Great earthquake (b) Safety limit earthquake (c) Damage limit earthquake

Figure 7 Comparison of response spectrum on box foundation (h=5%)



(a) Great earthquake (b) Safety limit earthquake

Figure 8 Comparison between response spectrum of box foundation and that of pile foundation

4. DYNAMIC ANALYSIS METHOD

4.1. Dynamic Analysis Model

This paper proposed the dynamic analysis method of the box foundation. It uses the lumped mass model considering the practicality. There is no generalized method for the dynamic analysis method of the box foundation using the lumped mass model. In this paper, the passive resisting springs and the friction springs of the continuous underground wall are modeled to evaluate characteristics of the box foundation. And also, the passive resisting springs and the friction springs of the internal soil side are modeled (Figure 9). The proposal dynamic analysis model is shown in Figure 10.

$$K_g = G_g \cdot A_g / l_g \tag{4.1}$$
$$K_f = G_f \cdot A_f / l_f \tag{4.2}$$

K_g : shear spring of internal soil, G_g : shear modulus of internal soil, A_g : sectional area of internal soil, l_g : layer thickness of internal soil, K_f : shear spring of free field, G_f : shear modulus of free field, A_f : sectional area of free field, l_f : layer thickness of free field

$$m_g = \rho_g \cdot A_g \cdot l_g \tag{4.3}$$
$$m_f = \rho_f \cdot A_f \cdot l_f \tag{4.4}$$

m_g : mass of internal soil, ρ_g : density of internal soil, m_f : mass of free field, ρ_f : density of free field, soil non-linearity is Ramberg-Osgood model.

$$h_r = \sin(0.5*\arctan(\mathrm{imag}(K_r)/\mathrm{real}(K_r))) \tag{4.5}$$

h_r : equivalent damping factor of rotational spring, K_r : rotational soil spring

4.2. Evaluation of Spring for Connection

The rigorous full matrices of the soil springs are calculated using the three dimensional thin layered element method in the beginning. These are reduced to shear soil springs, horizontal soil springs and dashpots. These are distributed to the passive resisting springs and the friction springs according to the area of the continuous underground wall. When distributing them, the weight coefficients are considered.

$$K_{p1} = K_a \cdot S_{p1} / S_a \tag{4.6}$$
$$K_{p2} = K_a \cdot S_{p2} / S_a \tag{4.7}$$

$$K_{f1} = K_a \cdot \gamma \cdot S_{f1} \,/\, S_a \tag{4.8}$$
$$K_{f2} = K_a \cdot \gamma \cdot S_{f2} \,/\, S_a \tag{4.9}$$

K_{p1}, K_{p2}, K_{f1}, K_{f2}, K_a : outside and inside soil passive resisting springs, outside and inside soil friction springs, total spring, S_{p1}, S_{p2}, S_{f1}, S_{f2}: area of continuous underground wall, $S_a = S_{p1} + S_{p2} + \gamma \cdot S_{f1} + \gamma \cdot S_{f2}$, γ: ratio of friction force and horizontal subgrade reaction for each unit area (0.7 from the result of Figure 3). The non-linearity is provided from the experiment result by the tri-linear model like Figure 11.

$$\alpha_{p1} = K_{ps} \,/\, (K_{pd} + K_{ps}) \tag{4.10}$$
$$\alpha_{f1} = K_{fs} \,/\, (K_{fd} + K_{fs}) \tag{4.11}$$

α_{p1}, α_{f1} : rigidity decreasing rate of second inclination on passive resisting spring and friction spring, K_{ps}, K_{pd}: standard stiffness and initial stiffness of passive resisting spring, K_{fs}, K_{fd}: standard stiffness and initial stiffness of friction spring

$$p_{p1} = p_{pmax} \cdot (K_{ps} \,/\, K_{pd}) \tag{4.12}$$
$$p_{f1} = p_{fmax} \cdot (K_{fs} \,/\, K_{fd}) \tag{4.13}$$

p_{p1}, p_{f1} : first breakpoint stress of passive resisting spring and friction spring

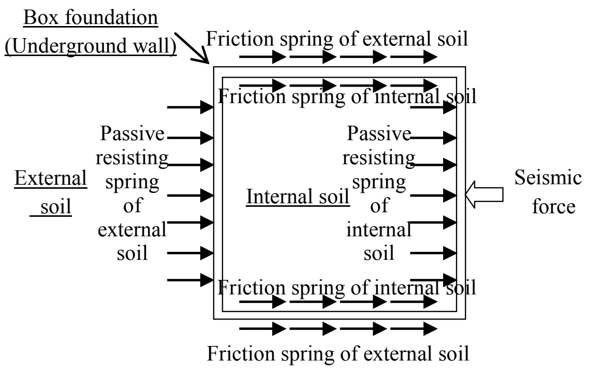


Figure 9 Outline of passive resisting springs and friction springs

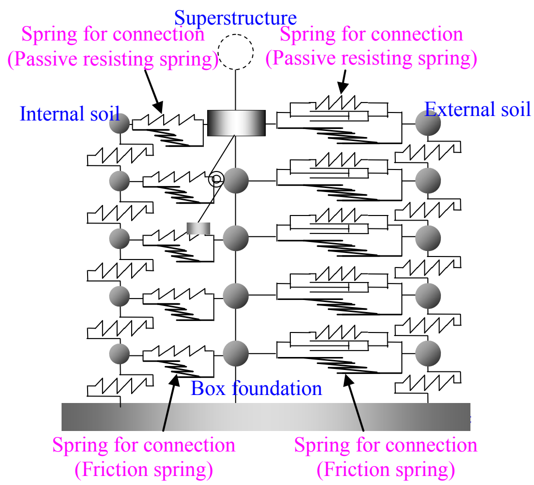
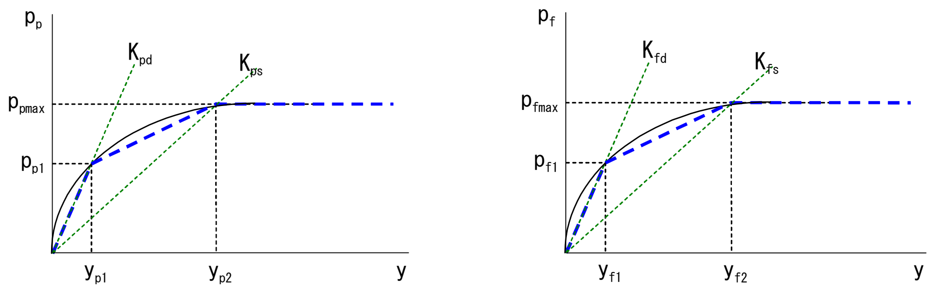


Figure 10 Proposal dynamic analysis model



(a) Horizontal subgrade reaction – displacement (b) Friction force - displacement

Figure 11 Non-linearity of springs for connection

5. COMPARISON BETWEEN ANALYSIS AND EXPERIMENT

5.1. Outline of Comparison

To confirm the validity of the proposal method, the simulation analysis is compared with the experiment result. For the box foundation without a superstructure, the proposal method is compared with the test result and the usual Penzien's model (The friction springs are not separated.), and for the box foundation with a superstructure, the proposal method is compared with the test result. The soil property is as showing in Table 1. The nonlinearity of that is Ramberg-Osgood model. The constant of that is provided by triaxial dynamic deformation tests.

5.2. Results of Comparison

The analysis results on the shear force of the continuous underground wall are shown in Figure 12. A horizontal axis is the maximum acceleration of soil surface at each excitation level. The result of the proposal method has adjusted to the result of experiment. Next, the analyses of earthquake excitation are shown. The input motion is shown in Figure 13. The comparison of waves between the proposal method result and the experiment result is shown in Figure 14. The comparison of those spectra is shown in Figure 15. The proposal method result has adjusted to the experiment result. As for the shear force of the continuous underground wall at GL-10m, the proposal method result is 55860kN, and the experiment result is 42140kN.

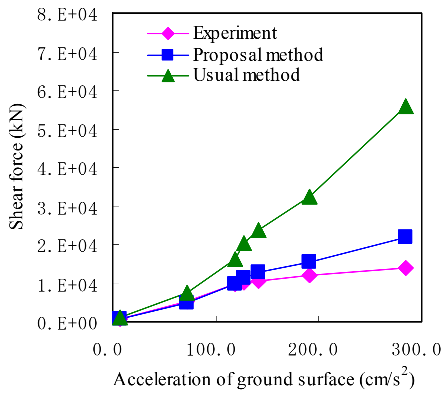


Figure 12 Analysis results on shear force of continuous underground wall

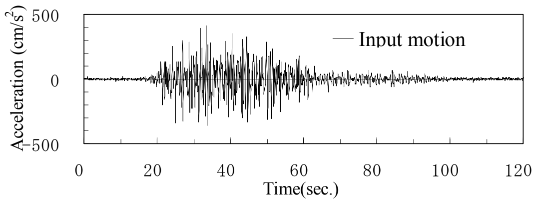


Figure 13 Input motion

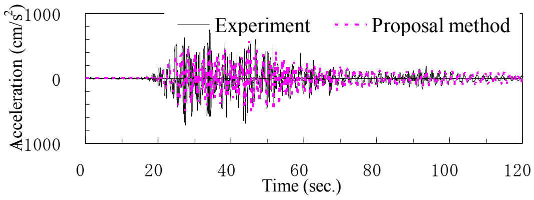


Figure 14 Comparison of waves between the proposal method result and the experiment result

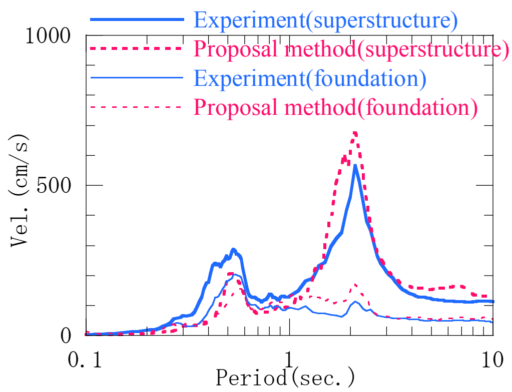


Figure 15 Comparison of response spectra between the proposal method results and the experiment results

6. CONCLUSIONS

The following findings were obtained.
1) The ratio of the friction force and the horizontal subgrade reaction of the continuous underground wall is about 0.7.
2) The friction force and the horizontal subgrade reaction reach the ceiling gradually.
3) The internal soil acceleration of the continuous underground wall is smaller than the external soil acceleration of that.
4) The response of the box foundation is smaller than that of the free field.
5) The increase rate of the maximum shear force of the continuous underground wall is smaller than the increase rate of the maximum acceleration.
6) The results of the proposal method have adjusted to the results of the experiment.

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