ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20230219000362
Original scientific paper

Dynamic Earthquake Response of 3-DOF Structure with Substructures by Centrifuge Test

Dong Kwan KIM, Ho Soo KIM, Jin Woo KIM*, Jin Young PARK

Abstract: In recent years, strong earthquakes have caused a lot of damage around the world. In order to prevent such damage, proper evaluation of the seismic performance of buildings is absolutely necessary. However, the current analysis procedure in seismic design assumes fixed boundary conditions for the foundation and neglects the influence of the substructure on the superstructure. Previous studies have shown that the type of foundation affects structural responses during earthquakes. However, most of these studies have focused on single-degree-of-freedom (SDOF) structures and have not considered variations in response according to different substructure types. This study aims to investigate the effects of different substructures on ground motion and corresponding responses of the superstructure. Centrifugal simulations were conducted on a multi-degree-of-freedom (MDOF) superstructure, including a Half-embedded with Pile foundation, a fixed deep basement, and a Shallow foundation. The experimental results indicate that in the case of a half-substructure with a pile foundation, there was no significant difference between free field motion and foundation motion due to the pile foundation. However, in the case of a fixed deep basement, the embedment effect was most pronounced, especially in the short period range of 0.1 s to 0.5 s in the response spectrum. This resulted in a notable reduction in the spectrum. The analysis of the response spectra of foundation motion and free field motion revealed that the reduction effect was absent in the half-embedded with a pile foundation, but it was prominent in the fixed deep basement. Notably, the ratio of response spectrum increased in the fundamental period of the substructure. In the case of a shallow foundation, it was observed that foundation motion experienced larger amplification compared to free field motion. Shallow foundations have a relatively low stiffness of the substructure and are influenced by the inertial forces of the superstructure. Additionally, this tendency is believed to be more prominent due to the imperfectly fixed boundary conditions of shallow foundations to the ground. However, apart from the increase in foundation motion, the response of the superstructure was not proportional to it. These results contribute to a better understanding of the changes in seismic load and the response of multi-degree-of-freedom superstructures according to the type of substructure. The seismic design of the superstructure is safer and more reasonable when considering the effects of the type of substructure.

Keywords: foundation embedment effect; kinematic interaction effects; Soil-Structure interaction; substructure

1 INTRODUCTION

The type of foundation affects structural response during earthquakes (see [14, 18]). In general, seismic design analysis procedures idealize the response of the structure by applying force to the structure, where the boundary conditions of the foundation are assumed to be on a fixed base. The forces applied to the structure are designed based on parameters for Free Field Motion (FFM). FFM refers to motion that is not affected by the vibration of a structure or the basic characteristics of a particular structure and is the condition under which a general design spectrum is derived. However, in most cases, the foundation motion (FM) transmitted to the structure may differ from that measured on the soil surface far away from the structure, and is affected by the vibration of the structure (see [12, 19]). These kinematic interactions have a major cause for base slab averaging and embedment effects. FEMA 440 considers Kinematic Interaction Effects, Flexible Foundation Effects, and Damping Effects for Soil-Structure Interaction (SSI)[7].

Feifei Sun et al. [6] studied how soil structure can affect the seismic mitigation performance of a periodic foundation. They found that the foundations can benefit from soil structure interactions, which can make them more effective at resisting seismic waves. One potential insight from this paper is that SSI plays an important role in the effectiveness of periodic foundations for mitigating seismic shaking. By taking SSI into account in the design and optimization of a periodic foundation, the foundation can be made more robust and less reliant on damping in resonators, which can improve the feasibility of the foundation. Another insight could be that, in order to optimize the seismic mitigation performance of the periodic foundation, it is necessary to consider SSI. It could also be seen as adding a case where the combination of specific foundations and soil types has optimal performance, and that proper design of the foundation needs to take this into consideration.

Hamid AG el al. [9] conducts a parametric study on the ductility and displacement demands of structures with embedded foundations in relation to nonlinear soil-structure interaction (SSI). The beam on Winkler foundation concept is used to simulate interactions between two objects. The behavior of the two objects is modeled using a bilinear behavior, which is assumed for the equivalent SDOF structure. This study looks at how different parameters, such as the fundamental period, level of inelasticity, soil flexibility, embedment ratio, and slenderness ratio, affect seismic demands. The analysis is done using a set of ground motions recorded on alluvium deposits. The results show that embedment generally makes the system more flexible, and that the kinematic interaction effect on ductility demands is more pronounced for structures with deep embedment ratios. In conclusion, nonlinear SSI can increase the displacement demand of interacting systems relative to an equivalent linear soil model. This highlights the importance of considering nonlinear soil-structure interactions in the design of structures, especially those with embedded foundations.

Amin Borghei et al. [1] discuss the results of a series of centrifuge experiments on foundation-structure models in their paper. The Kinematic Interaction Transfer Function (KITF) is a measure of how foundation input motion affects free field motion. This is often used in studies of how buildings move in response to changes in foundation movement. The Inertial Interaction affects how much lateral and rocking motion occurs around structural flexible-base natural frequencies. This means that the dynamic properties of the foundation-structure model are important to consider when evaluating the transfer functions. The findings suggest that the dynamic properties of the foundation-structure model and actual soil conditions should be taken into account when evaluating the transfer functions, and that the discrepancy between measured foundation motion and hypothetical foundation input motion can be predicted by measuring soil properties. It also highlights the limitations of using existing models, and that to achieve accurate results, the physical properties of the foundation-soil-structure system should be considered.

Korea has a narrow land area and a higher population density compared to other countries. Due to these national characteristics, most buildings include large structures such as large parking facilities and public facilities underneath. Recently, there have been many reports of damage to substructures caused by earthquakes around the world, and in line with this trend, the Code for Seismic Design of Substructures (KDS 41 17 00) [2] has been developed. However, due to the diverse substructures and the lack of relevant research, the criteria do not include seismic design codes that consider SSI. Despite being known as an earthquake-safe country, Korea has been increasingly in demand for seismic design technologies because of recent earthquakes such as Gyeongju (2016; M_w = 5.8) and Pohang (2017; M_w = 5.4), and demands for reasonable seismic performance evaluation methods are increasing as buildings become larger and taller.

In this study, centrifugal model tests were conducted on 3-DOF structures with half-embedded pile foundations, fixed deep basements, and shallow foundations. Through the experimental results, the difference between free-field motion and foundation motion was compared and analyzed, and the response of the superstructure according to each substructure type was analyzed. In line with this, the study was conducted for the purpose of comparing the seismic load and the response of the superstructure according to the type of substructure.

2 SOIL-STRUCTRE INTERACTION

2.1 Fema 440

FEMA 440 includes the effects of Flexible Foundation Effects, Kinematic Effects, and Foundation Damping Effects in non-linear static analysis procedures considering SSI [7]. For buildings that contain substructures, the ground motion acting on foundation slabs may differ from the free field motion, and this effect is related to wave scattering and embedded effects. This effect tends to be important for short fundamental periods (i.e., periods less than ~0.5 s) and large plan dimensions, and bases embedded in over 10 ft.

Fig. 1a, Eq. (1) represents the Rratio of Response Spectra (*RRS*) between free-field motion and foundation motion for effective foundation size. As the foundation size increases, the foundation motion decreases compared to the free-field motion. Fig. 1b, Eq. (2) shows the kinematic effects according to foundation embedment and site soil conditions. As the basement embedment increases, the *RRS* decreases, and when the shear wave velocity for site soil conditions is small or the periods are less than 0.5 s, the *RRS* decreases significantly. As the periods increase, the *RRS* converges to 1.

$$RRS = 1 - \frac{1}{14.100}\left(\frac{b}{T}\right) \geq \text{ the value for } T = 0.2 \text{ s} \tag{1}$$

$$RRS = \cos\left(\frac{2\pi e}{Tnv}\right) \geq 0.435 \text{ or the } RRS \text{ value for } T = 0.2 \text{ s} \tag{2}$$

where b_e is the Evaluate the effective foundation size, $b_e = \sqrt{ab}$ where a and b are the full footprint dimensions (in feet) of the building foundation in plan view, e is foundation embedment, v_s is shear wave velocity for site soil conditions, n is shear wave velocity reduction factor for the expected PGA

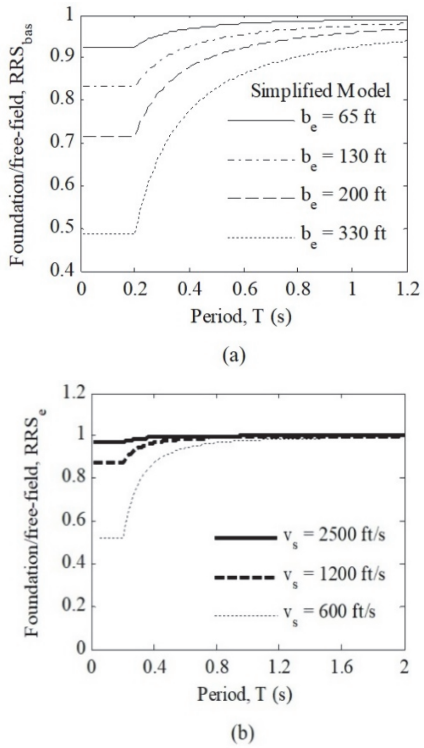


Figure 1 Kinematic Interaction efects in FEMA 440; (a) Ratio of response spectra for base slab averaging, RRS_{bas}; (b) Ratio of response spectra for embedment RRS_e

2.2 Fema P-1050

FEMA P-1050 describes the procedures and theories that reflect the effects of SSI in seismic design [8]. In an earthquake, the shaking is transmitted through the structure from the geologic media underlying and surrounding the foundation. This affects how the building responds to the earthquake shaking. There are three important pieces to this puzzle: the building, the foundation, and the ground below and surrounding the foundation. In general seismic design, analysis procedures idealize the response of the structure by applying force to the structure, where the boundary conditions of the foundation are assumed to be on a fixed basis. The force applied to the structure is calculated through parameters representing free-field motion. However, in most cases, the foundation motion transferred to the structure is different from free-field motion. These differences are due to the interaction of structures and geologic media. In FEMA P-1050, the interaction between geologic media and structures is considered through foundation deformations, inertial interaction effects, and kinematic effects. Eq. (3) indicates the foundation embedment effect in kinematic interaction.

$$RRS = 0.25 + 0.75 \times \cos\left(\frac{2\pi e}{Tv}\right) \geq 0.50 \tag{3}$$

where e is foundation embedment depth (m), v_s is shear wave velocity for soil conditions (m/s). T is response spectra period. Fig. 2 shows the expected base slab averaging effect and foundation embedment effect of the experiments used in the centrifuge model test performed in this study.

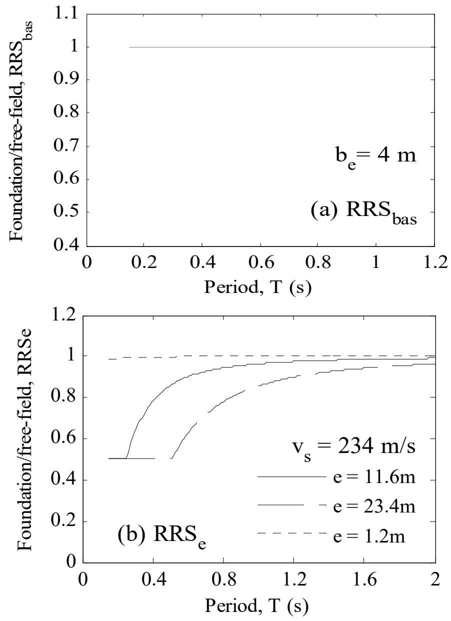
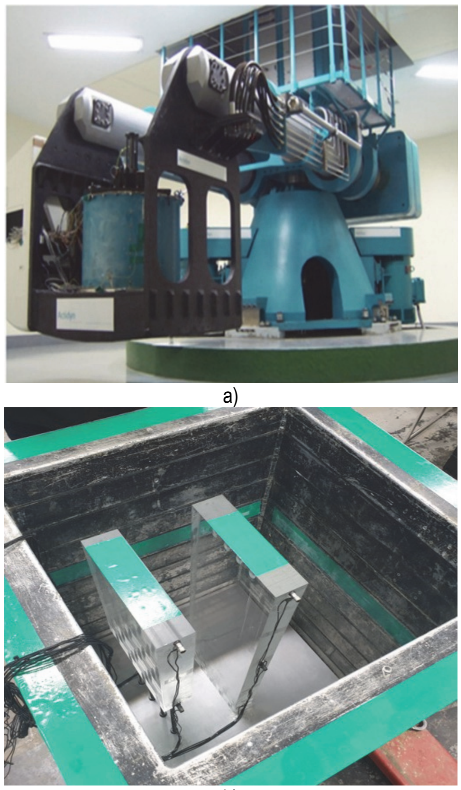


Figure 2 Expected kinematic interaction effects of the specimen structure: (a) Ratio of response spectra for base slab averaging, RRS_{bas} (FEMA 440); (b) Ratio of response spectra for embedment RRS_e (FEMA P-1050)

3 EXPERIMENTAL METHOD
3.1 Centrifuge Model Test

In this study, the researchers conducted a centrifuge model tests to evaluate the effects of superstructure due to Soil-Structure Interaction Fig. 3. The centrifuge model test is an experiment that simulates the stress state of reduced soil. When rotated with N times centrifugal acceleration (N_{qc}), the stress distribution on the soil appears the same at the 1/N times reduced depth [10].

The soil container used in this study is designed to reduce the reflection of waves at the boundary of the container. The container, which has external and internal dimensions of 0.6 × 0.6 × 0.63 m and 0.49 × 0.49 × 0.6 m in Fig. 5, was mounted on a shaking table attached to the centrifuge apparatus. Each frame was 60 mm in height and separated by inside ball bearings and rubber spacing layers. For 40 g centrifugal acceleration, the prototype soil size corresponded to 19.6 × 19.6 × 24 m [4].



a)

b)

Figure 3 Centrifuge Test: (a) Artificial gravity unit (in Korea's KAIST university) ; (b) Substructure installed in Equivalent Shear Beam Box (ESB)

3.2 Specimen Structure

In this procedure, a three-floor, multi-DOF specimen structure with three substructures was tested: Half-embedded with Pile Foundation, Fixed Deep Basement, and Shallow Foundation. Before the centrifuge model test, the fundamental period was measured through an impact hammer test, as shown in Tab. 1. Steel was used for the superstructures, and acrylic materials were used for the substructures, considering the rigidity of the substructures. A total of 18 accelerometers were used for measuring as shown in Fig. 4 (see [17, 23]).

Table 1 Experimental variable of structure (in a state of 40 g)

Structure	Marterial	Weight / kN	Mode	Period Test / s	Frequency / Hz
Upper Structure	Steel	28.94	1st	1.52	0.658
			2nd	0.76	1.316
			3rd	0.40	2.500
Fixed Deep Substructure	Acrylic	68.22	1st	0.12	8.33
Half Substructure	Acrylic	33.82	1st	0.08	12.50
Half Substructure with Pile foundation	Acrylic and Steel	34.59	1st	1.36	0.74

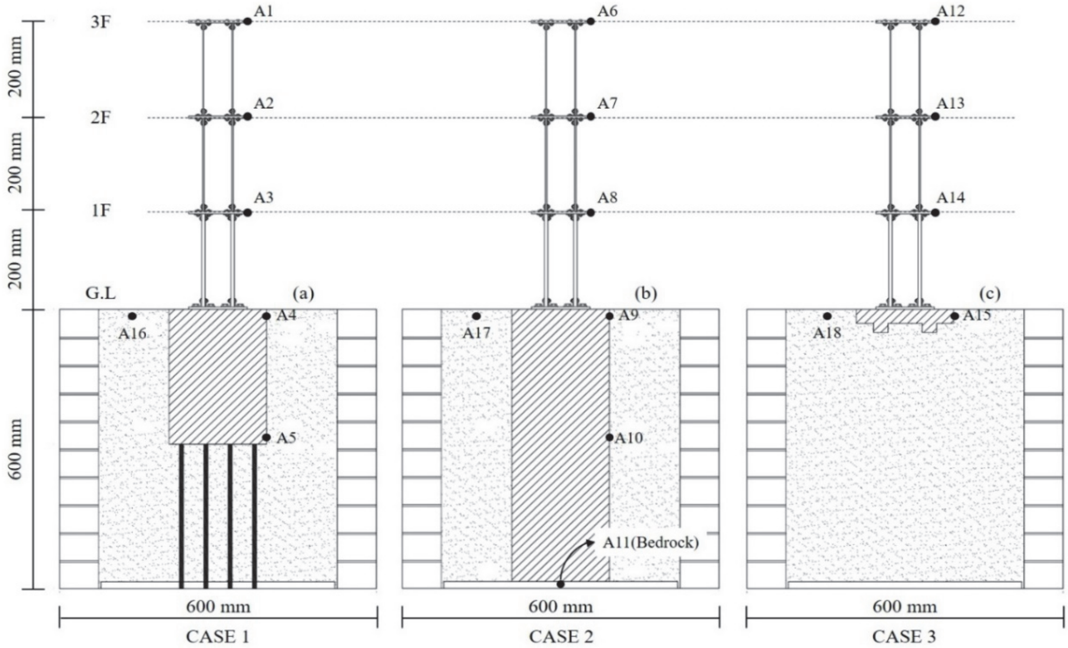
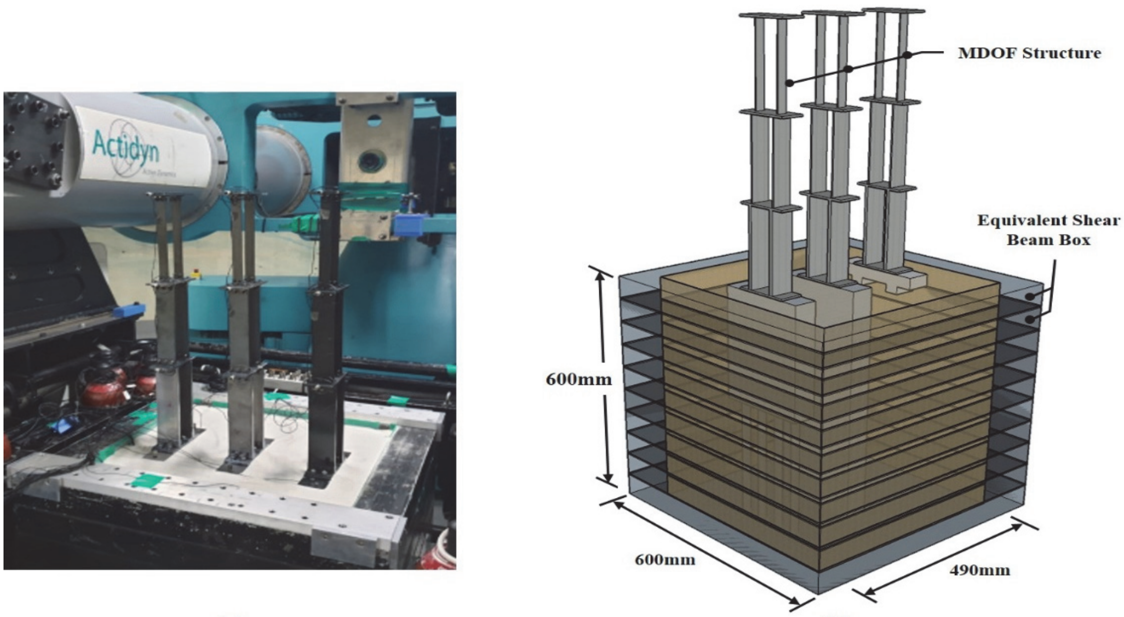


Figure 4 Test model: (a) CASE 1: half-embedded with pile foundation; (b) CASE 2: fixed deep basement; (c) CASE 3: shallow foundation



(a) (b)

Figure 5 Test Specimen installation: (a) test specimen; (b) installation plan

3.3 Soil Properties

Silica sand was chosen for the testing program. A sand-rainer was used for uniform distribution. The sand had a relative density of approximately 80%, and the density was 1.55 t/m^3. The shear-wave velocities (V_S) of the soil were estimated from the bender element tests. The shear-wave velocities measured at 20 gc and 40 gc were 185 m/s and 234 m/s, respectively. The elastic site period (T_{soil}) of the prototype soil can be calculated using Eq. (4). The site period was estimated as 0.41 s at 40 gc [16].

$$T = \frac{4D}{V} \tag{4}$$

where D and V_s are the thickness and the shear-wave velocity of prototype soil.

3.3 Input Accelerations

To calculate the input seismic wave for this experiment, 301 seismic records with a Richter magnitude of 5.0 or greater were collected from the rock earthquake records provided by the World Earthquake Database (PEER [20], USGS [24], ESMD [5]). The response spectrum acceleration of the collected seismic records was derived, and the scale factor was calculated and reflected to a similar size as the S_1 rock spectrum of the KDS 41 17 00. Among the adjusted rock earthquake records, the four rock seismic records with the smallest Mean Squared Error (*MSE*) were used as input seismic waves, as shown in Fig. 6.

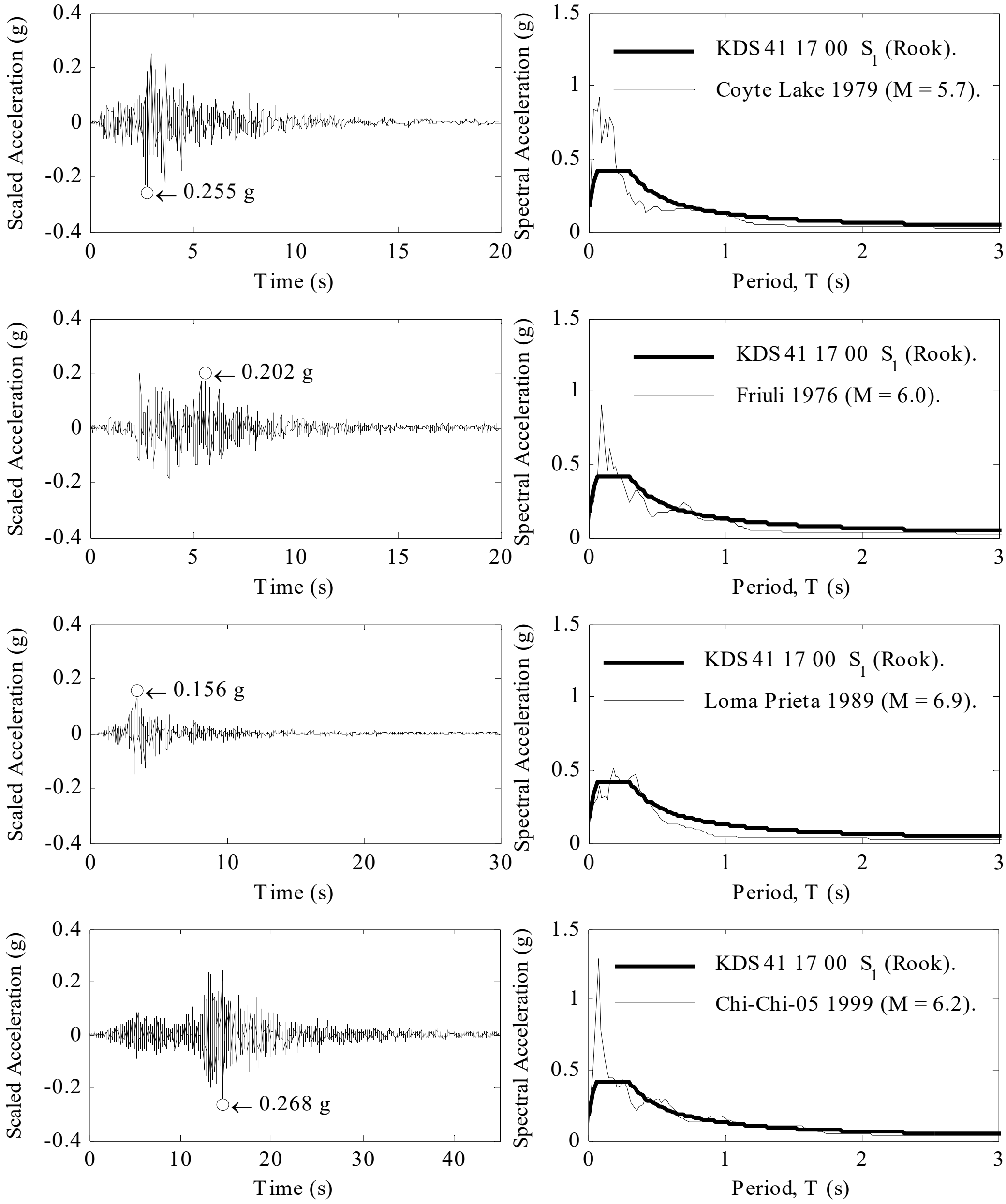


Figure 6 Input seismic waves

4 SEISMIC AMPLIFICATION EFFECT CONSIDERING SSI
4.1 Kinematic Interaction Effect

Fig. 7 shows the free field motion and foundation motion, as well as the response spectrum acceleration according to the type of substructure. In the case of the pile foundation in Fig. 7a, a reduction effect was expected due to the foundation embedment effect, but the difference between free field motion and foundation motion, as well as the Response Acceleration Spectrum, was not significant. This is due to the influence of the pile foundation fixed on bedrock, and the fundamental period of the half-substructure with the pile foundation is 1.36 s longer than the fundamental period (0.41 s) of the soil, which is a relatively long period. Therefore, the rigidity of the lower structure is difficult to manifest, so it is judged that the dominant effect was caused by the soil, and that there was no reduction effect by the embedment effect. With the Fixed base in Fig. 7b, the reduction effect by the foundation effect was noticeable. However, the reduction effect for foundation motion is most evident in the short period (0.1 s to 0.5 s), and the decrease in the mid- to long period did not occur. In addition, the period of 0.41 s, corresponding to the period of the soil, was found to have the same amplification in free field motion and foundation motion. In the case of the shallow foundation in Fig. 7c, the foundation motion was larger than the free field motion. It is considered that since there are no substructures, the foundation motion is not affected by the embedment effect and the foundation motion occurs with a larger amplification than free field motion due to its relatively small rigidity (see [3, 25]).

Fig. 8 shows the Ratio of Response Spectrum (*RRS*) between foundation motion and free field motion. The overall *RRS* trend is consistent with the time history analysis and response spectrum analysis of foundation motion and free field motion. Also, a comparison of *RRS* through the test results and RRS_e presented in FEMA P-1050 showed no reduction by foundation embedment effect for Pile foundation, resulting in a different outcome from RRS_e. These results indicate, that for a substructure with a pile foundation, there may not be a reduction effect due to the foundation embedment effect [21]. With the fixed basement, the maximum reduction rate in the short period (0.1 s to 0.5 s) was similar, but the range of period was not correct. These results show that at 0.12 s corresponding to the fundamental period of the substructure and 0.41 s, the fundamental period of the ground, the *RRS* may result in an amplification exceeding 1.

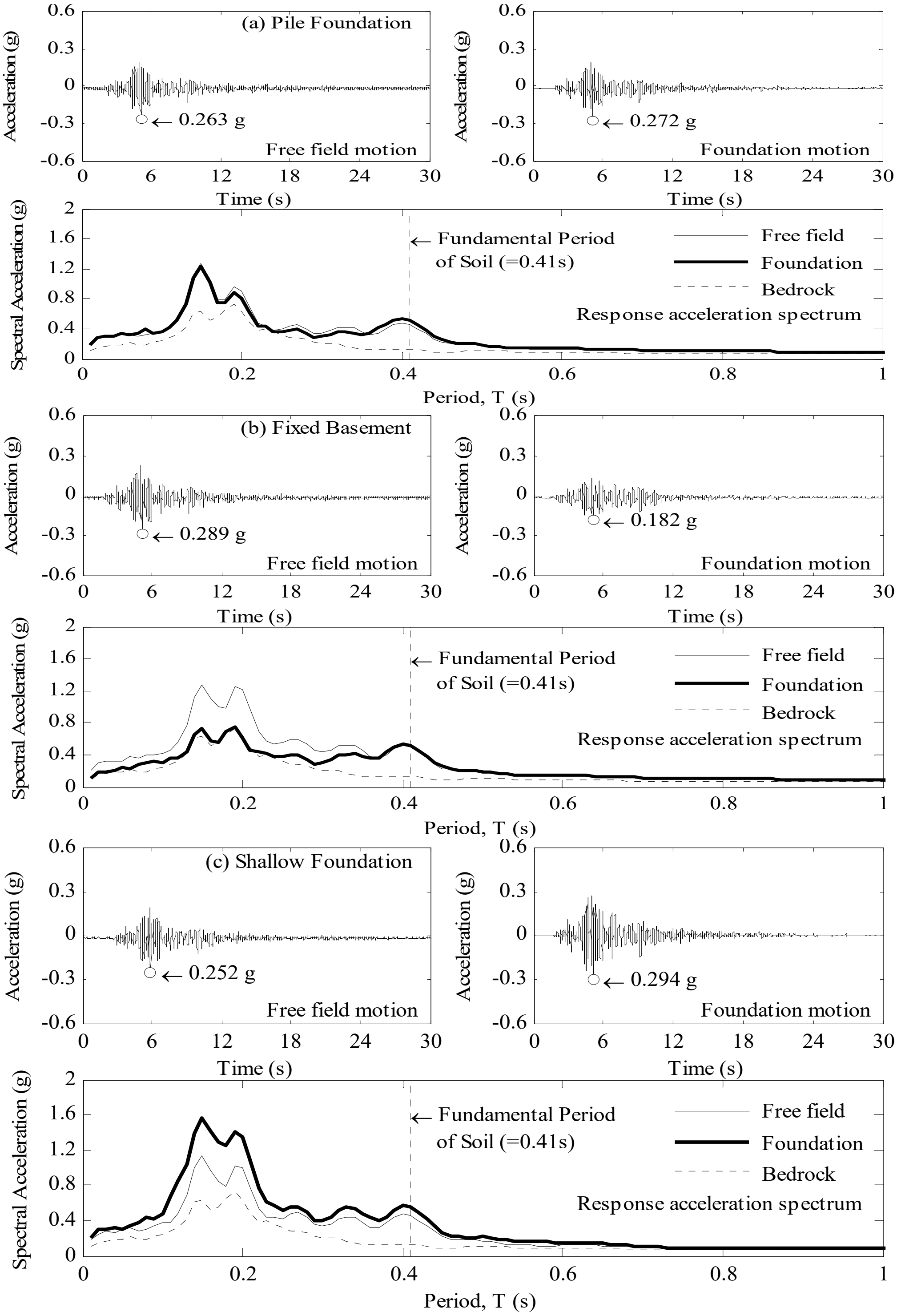


Figure 7 Response acceleration spectrum of free-field motion and foundation motion; (a) pile foundation, (b) fixed basement, (c) shallow foundation

4.2 Seismic Response Reduction Ratio

Tab. 2 represents the average variance rate of *RRS*. In short periods (0.1s to 0.5s), there is a difference in size according to the seismic wave, but the *RRS* decreases in the fixed basement, and hardly appears in the pile foundation. With the shallow foundation, it was shown to increase by more than 10%. Fig. 9 shows the overall *RRS* rate of variance in the test. The mid-period (0.5s to 1.0s) and long-period (1.0s to 2.0s) did not show significant variance rat

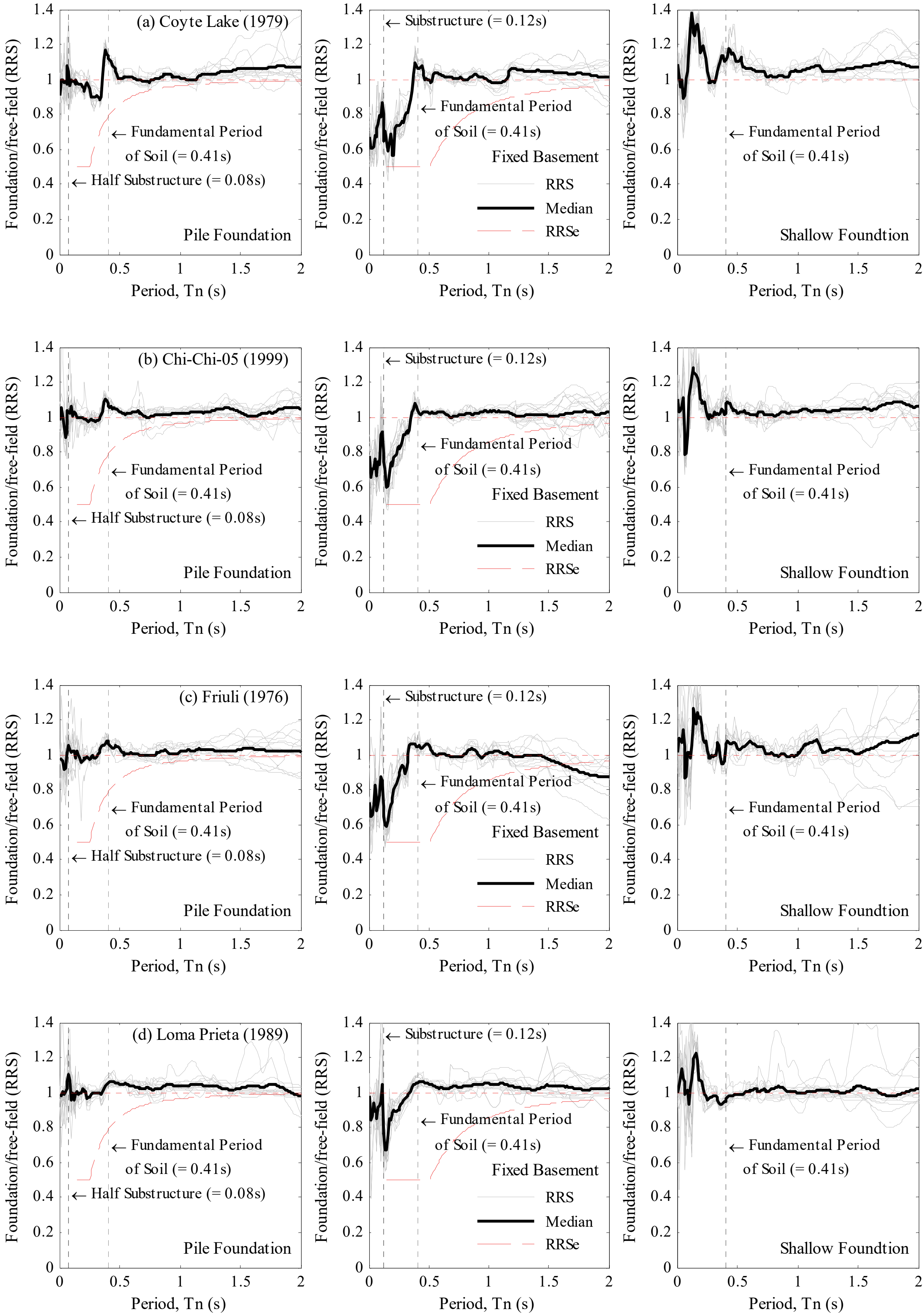


Figure 8 Foundation/free-field motion ratio (*RRS*)

Table 2 Average *RRS* variance rate

Event	Substructure	Average Variance Rate of *RRS*		
		0.1 s ~ 0.5 s Rate	0.5 s ~ 1.0 s Rate	1.0 s ~ 2.0 s Rate
Coyte Lake	Pile Foundation (PF)	0.98	1.01	1.02
	Fixed Basement (FB)	0.75	1.01	1.01
	Shallow Foudnation (SF)	1.20	1.05	1.06
Chi-Chi-05	Pile Foundation (PF)	1.02	1.02	1.03
	Fixed Basement (FB)	0.86	1.02	1.03
	Shallow Foudnation (SF)	1.13	1.02	1.04
Friuli	Pile Foundation (PF)	1.01	1.01	1.03
	Fixed Basement (FB)	0.85	1.00	1.00
	Shallow Foudnation (SF)	1.13	1.04	1.05
Loma Perieta	Pile Foundation (PF)	1.02	1.04	1.04
	Fixed Basement (FB)	0.97	1.04	1.04
	Shallow Foudnation (SF)	1.01	1.01	1.01

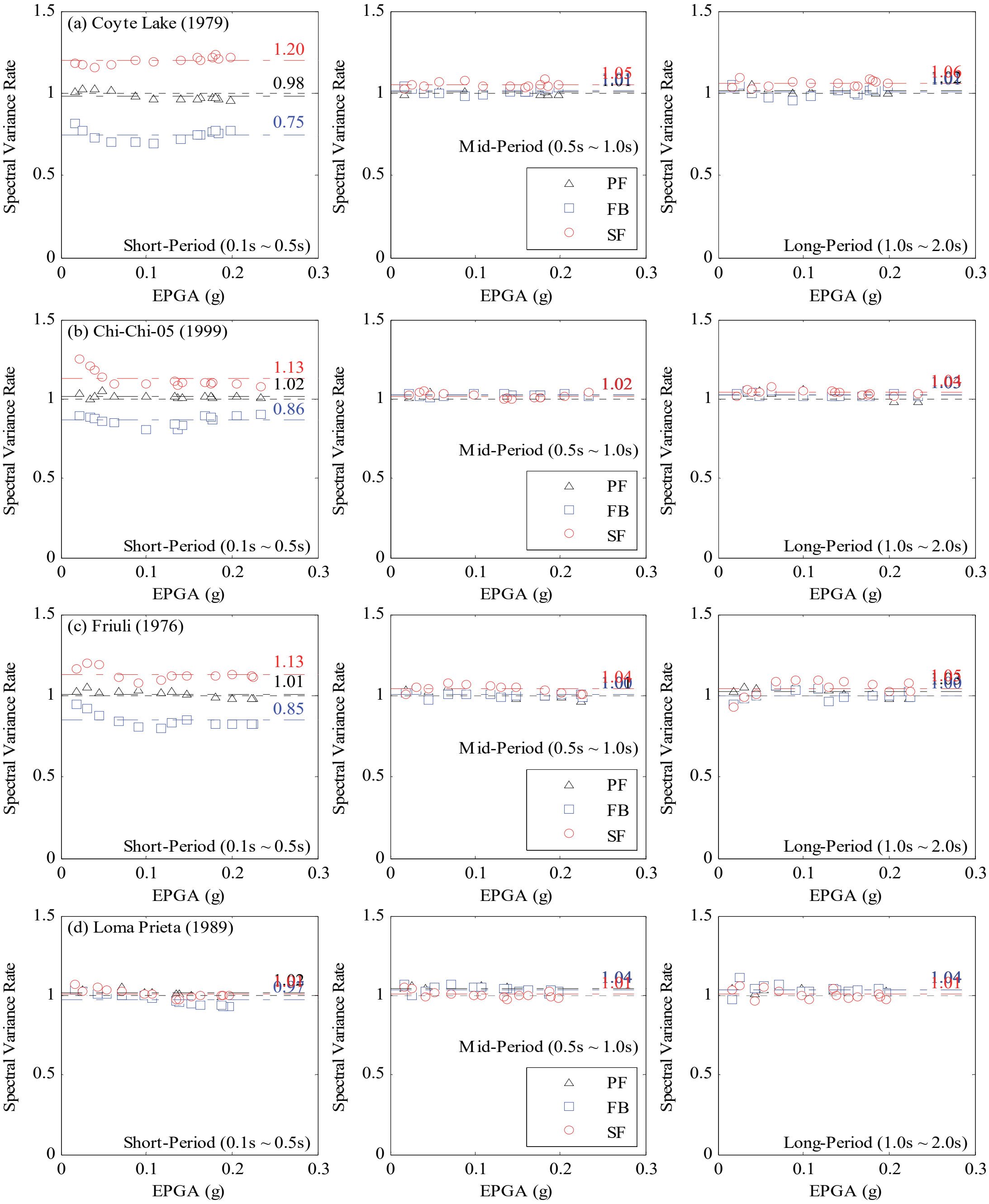


Figure 9 Variance rate of response spectrum

4.3 Foundation Damping

In calculating the damping ratio, there is a general method for calculating it by using the free vibration curve in the time history record, assuming that the target structure has the form of viscous damping. However, since the measured time history waveform is generally complex and several vibration components appear together, it is difficult to calculate the damping ratio by using the time history waveform alone. Therefore, in this study, the damping ratio is estimated using the Half-Power Bandwidth as shown in Eq. (5) [22].

$$\beta = \frac{\beta_b - \beta_a}{2 \times f} \tag{5}$$

where β is damping ratio, f_n is frequency at maximum amplitude, β_a and β_b are respectively lower and upper frequency of the maximum amplitude multiplied by $1/\sqrt{2}$. Foundation damping according to the substructure type is shown in Tab. 3.

Table 3 Foundation damping ratio using half-power bandwidth

Substructure	EPGA / g	f_n / Hz	β_a / Hz	β_b / Hz	Damping
Pile foundation	0.050	1.300	1.283	1.316	0.0128
	0.119	1.300	1.285	1.328	0.0164
	0.199	1.300	1.263	1.354	0.0351
Fixed basement	0.050	1.300	1.281	1.342	0.0232
	0.119	1.300	1.286	1.337	0.0199
	0.199	1.300	1.264	1.359	0.0364
Shallow foundation	0.050	1.300	1.282	1.350	0.0260
	0.119	1.300	1.285	1.327	0.0164
	0.199	1.333	1.274	1.362	0.0327

5 RESPONSE OF SUPERSTRUCTURE

5.1 Frequency Analysis

The researchers performed frequency analysis on the seismic response of each floor. The natural frequency of vibration components was similar to the natural frequency through the impact hammer test. In particular, the pile foundation and fixed basement were shown to match the fundamental frequency by the test, but the fundamental frequency of the shallow foundation was reduced due to the period-lengthening effect. Looking at the vibration mode that affects each floor, it is judged that the effect of the first mode is not significant because the vibration component corresponding to the first mode is not large in all floors. In the case of the first floor, the influence of the third vibration component is predominant, and the second and third vibration components were simultaneously shown. The third floor showed the largest secondary vibration component.

Fig. 10 shows the transfer function of foundation motion and bedrock motion. Amplification appears in the frequency domain corresponding to the fundamental frequency of each substructure type. In particular, the shallow foundation shows the greatest amplification at the fundamental frequency of soil. Through this, it is determined that the fundamental period of the substructure affects the ground motion.

5.2 Time History Acceleration Response

Fig. 11 to 13 show the acceleration time history response according to the substructure type. The maximum acceleration in the foundation was found to be the most amplified at 0.458 g, 0.400 g, and 0.524 g respectively in the shallow foundation in Fig. 13g. In the case of the shallow foundation, the maximum acceleration was the largest due to the amplification by the soil and relatively small stiffness. In the case of the fixed basement, since the structure is directly supported by the bedrock, it is believed that the effect of ground amplification by the soil is reduced and the damping effect is according to the rigidity of the substructure. In the case of half-embedded with pile foundation, it was found to be an intermediate value between the shallow foundation and fixed basement results because it is affected by the soil and pile foundation. In the maximum acceleration of the superstructure, the maximum was 0.420 g (3F), 1.058 g (2F), and 1.192 g (1F) in the fixed basement in Fig. 12. In particular, the foundation motion was the largest in the shallow foundation, but the response of the superstructure was 0.281 g (3F), 0.946 g (2F) and 1.204 g (1F), which was found to be smaller than the other cases. Unlike the other two substructures, the shallow foundation is in a state where the lower part is not fixed, so it is judged that the response of the superstructure has decreased due to the period-lengthening effect.

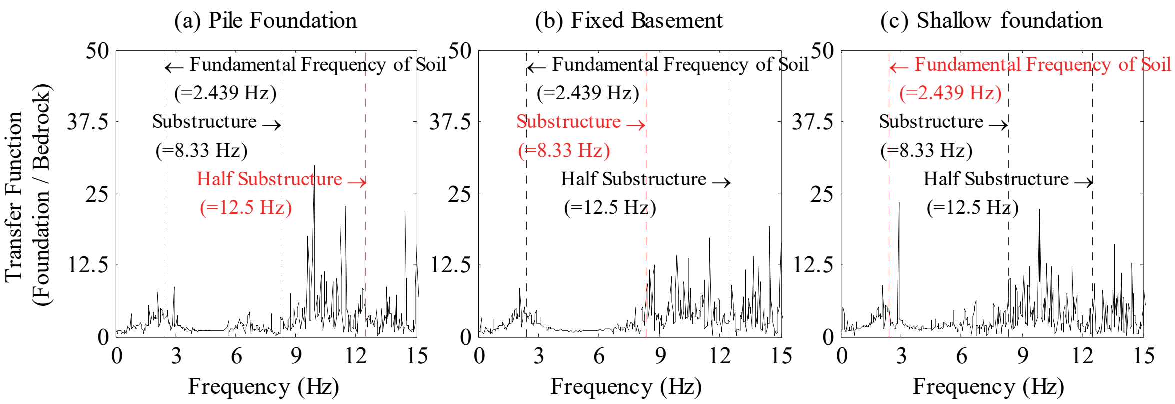


Figure 10 Transfer function by substructure type

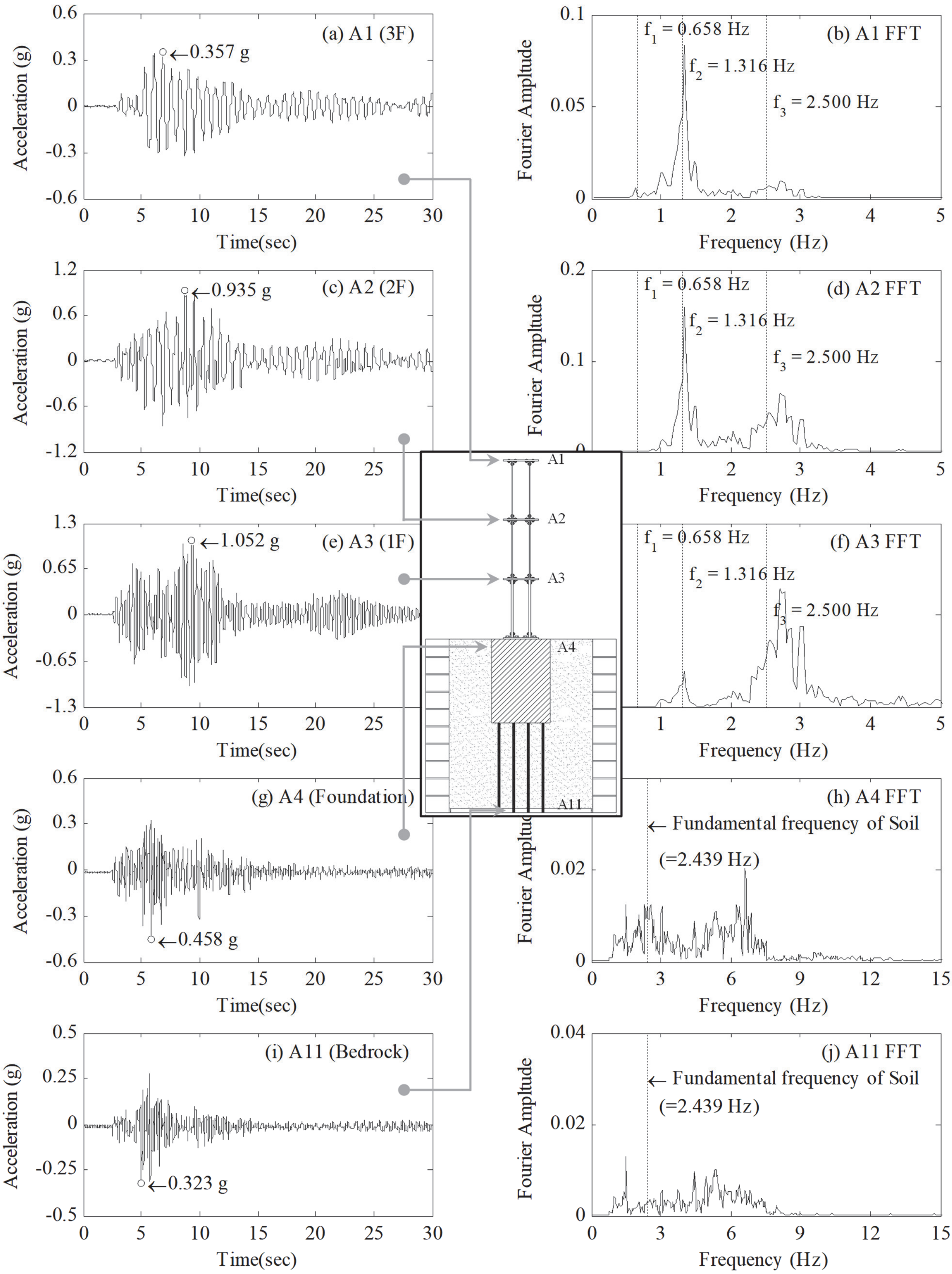


Figure 11 Pile foundation time history result

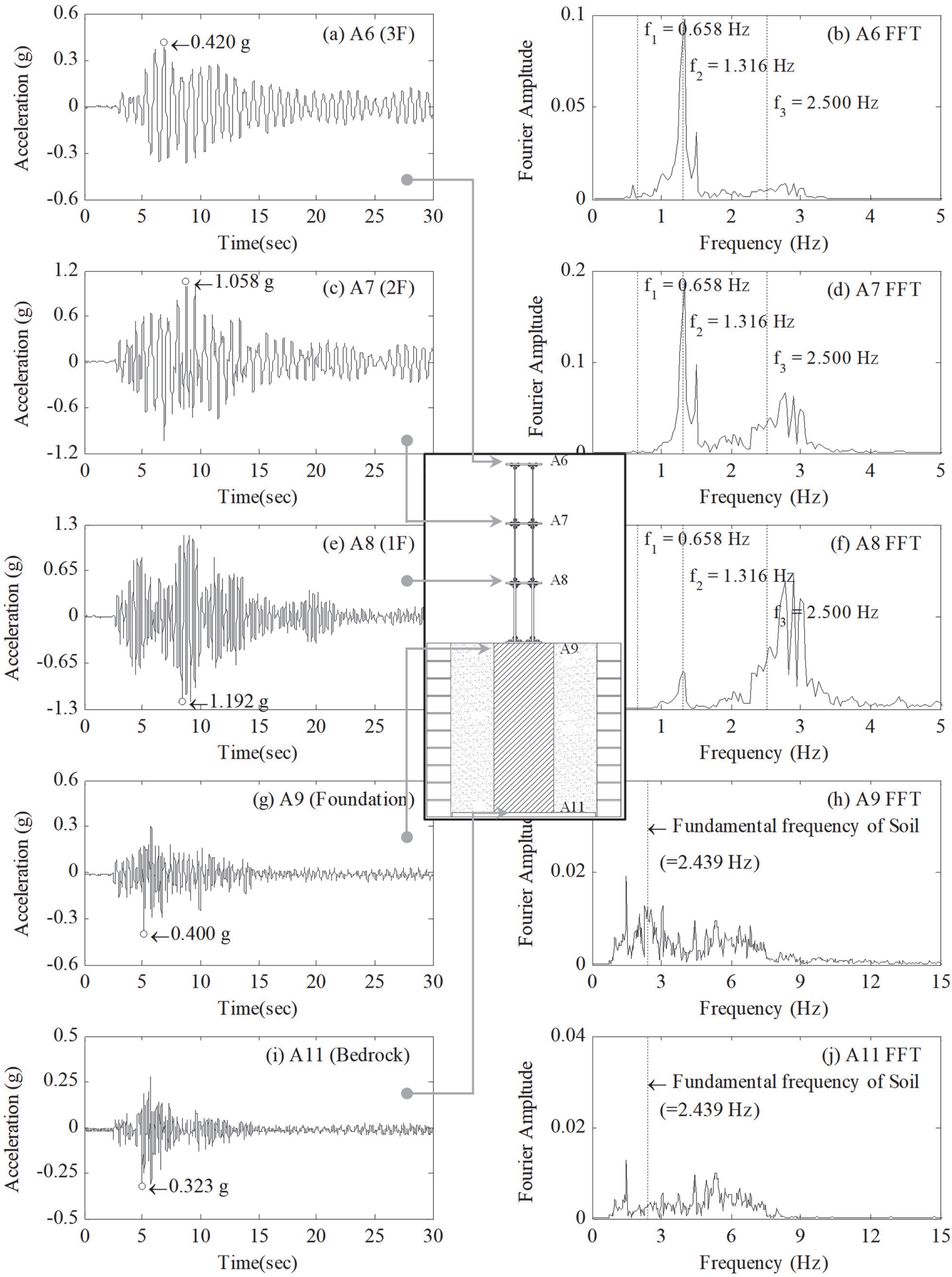


Figure 12 Fixed basement time history result

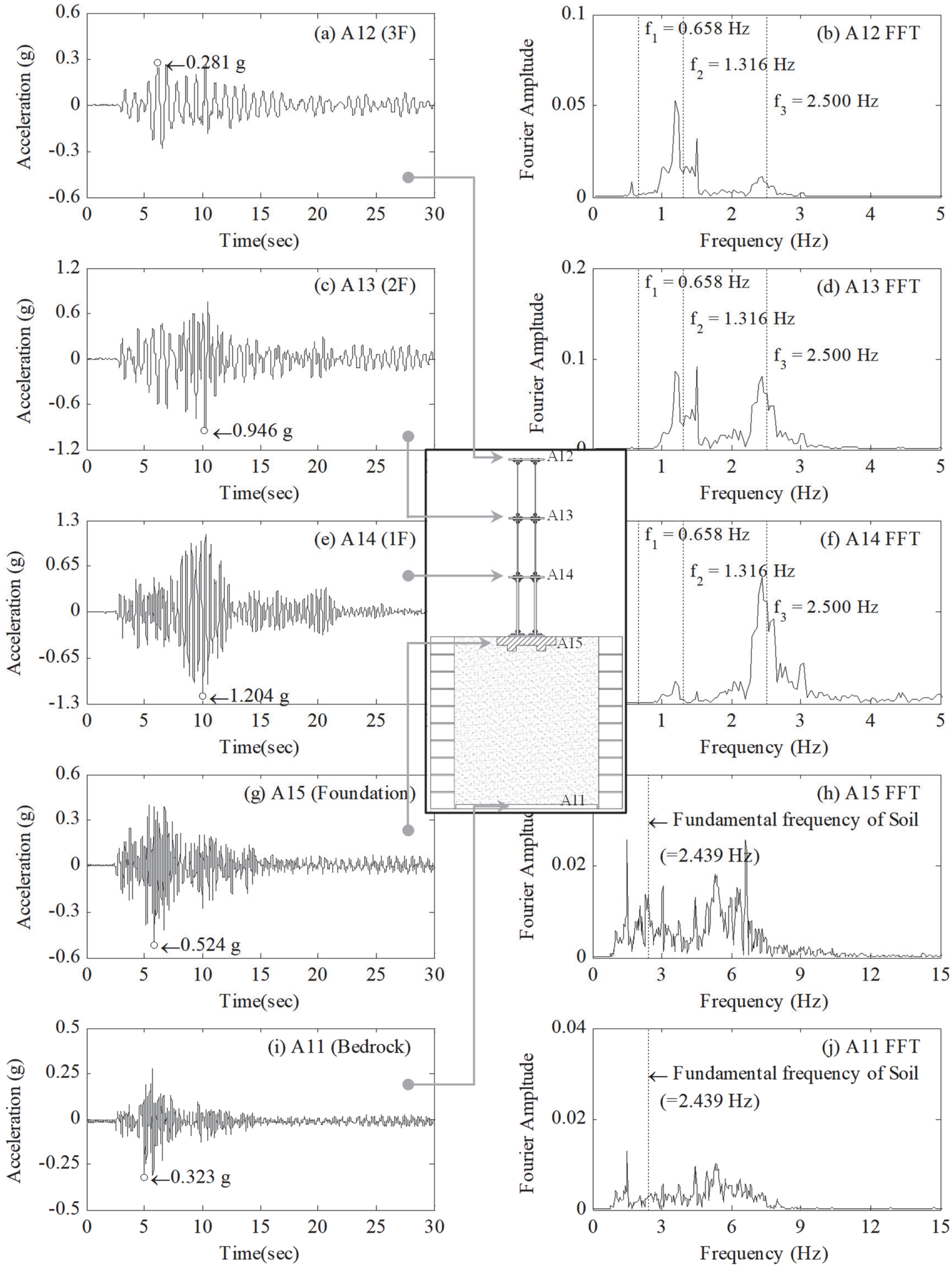


Figure 13 Shallow foundation time history result

6 RESULTS AND DISCUSSION

In this study, centrifuge model tests were conducted to investigate the seismic load on the substructure and the response of the superstructure according to the substructure type. The comprehensive results of the centrifuge model tests are as follows: For half-embedded substructure with pile foundations, there was no significant effect of kinematic interaction. Consequently, there was no difference between the free-field motion and the foundation motion. These results can be attributed to the inherent vibration period of the substructure with pile foundation. The natural vibration period of the substructure with pile foundation but excluding the soil was measured as 1.36 s. This value corresponds to a much longer period compared to the natural vibration period of the soil, which is 0.41 s. This difference in natural vibration periods implies that during an earthquake, the displacement of the substructure with pile foundation is larger than the ground displacement. However, in reality, the displacement of the substructure cannot be larger than the ground displacement [15]. Due to this reason, the free-field motion and the base motion showed consistent results in the response spectrum, and there was no observed spectrum reduction effect due to the kinematic interaction of the underground structure. The spectral reduction effect due to kinematic interaction effect was most prominently observed in fixed deep basements. However, this effect is more pronounced in the short period range of less than 0.5 s. No spectral reduction effect was observed in the medium to long period range exceeding 0.5 s. Unlike the reduced response spectra, the response of the superstructure containing the fixed deep basement did not significantly decrease. In the frequency analysis, the vibration mode period that had the greatest influence on the response of the superstructure was the second mode with a period of 0.76 s. This value is larger than the period of less than 0.5 s, where the spectral reduction occurred due to kinematic interaction effect. Therefore, it can be concluded that there was no response reduction effect in the long-period superstructure of the tested specimen. In the case of a shallow foundation, there is no basement, eliminating the possibility of kinematic interaction effects. Initially, it was expected that free-field motion and foundation motion would have little difference [11]. However, it turned out that the amplification in foundation motion is even greater than that in the free-field motion, as evident in the response spectrum. Shallow foundations have very low substructure stiffness and incomplete coupling with the ground's boundary conditions. Consequently, they exhibit less resistance to horizontal displacement and are more susceptible to the inertial forces acting on the superstructure. This susceptibility is believed to be the reason for the increased foundation motion compared to free-field motion [13]. However, unlike the increase in foundation motion, the response of the superstructure did not proportionally follow. Instead, it was observed that the response in the upper layers decreased in comparison to other cases. This can be attributed to the vulnerability of deformations in shallow foundations.

7 CONCLUSIONS

This study was conducted to compare the seismic load and response of the superstructure based on different substructure types. A centrifuge model test was performed on a 1/40 scale model to evaluate the ground motion, considering soil-structure interaction and the response of the multi-DOF (Degrees of Freedom) superstructure. The response ratio spectrum of free field motion and foundation motion was analyzed using measurement records, leading to the following conclusions.

1) We analyzed the *RRS* (Ratio of Response Spectrum) for free-field motion and foundation motion according to each substructure type. There was no significant difference in the *RRS* for the half-embedded basement with pile foundations. Fixed deep basement showed a maximum 25% reduction in free-field motion in the short-period range (less than 0.5 s). However, there was no significant effect in the medium to long-period range. For shallow foundations, the base motion was found to increase by a maximum of 20% compared to free-field motion.

2) In the *RRS* analysis, we confirmed amplification occurring at the natural frequencies of each underground structure. This was also observed in frequency analysis. These results indicate that seismic loads may increase at the natural frequencies of underground structures.

3) Half-embedded basement with pile foundations was not affected by kinematic interaction effects. The natural frequency of the substructure with pile foundation was measured at 1.36 s. This corresponds to a much longer period than the natural frequency of the ground, which is 0.41 s. Therefore, it is concluded that the stiffness of the substructure is difficult to express, leading to the same response for free-field and foundation motion.

4) In the case of fixed deep basements, the spectral reduction effect due to kinematic interaction effects was observed most prominently. However, this effect is more noticeable in the short-period range (less than 0.5 s). Despite the significant spectral reduction in the foundation level, the response of the upper structure, which includes the fixed deep foundations, did not decrease. The reason for this is that the dominant natural frequency of the superstructure's vibration modes was found to be 0.76 s, which is greater than 0.5 s.

5) For shallow foundations, larger amplification was observed in the foundation motion compared to free-field motion. This is because it is difficult to expect significant stiffness in the substructure, and the boundary conditions between the foundation and the ground are incomplete, leading to the transfer of inertial forces from the superstructure to the foundation motion. However, the response of the superstructure did not increase proportionally with the increase in foundation motion. This phenomenon is attributed to the response reduction of the superstructure due to the deformation of the foundation (period-lengthening effect).

6) In this experimental research, the results indicate that ground-structure interaction effects can vary depending on the type of underground structure and the superstructure. Specifically, when pile foundations are present, special attention needs to be given to the natural vibration period of the basement with pile foundations. Furthermore, caution is required when applying kinematic interaction effects to long-period structures with fixed deep basements. In this study, three experiments were conducted in a single soil box. The researchers conducted an experiment on the 1 - axis to minimize the structure-soil-structure interaction effect, but there is no guarantee that the structure-soil-structure effect did not appear completely. The results of this experiment are to compare the responses of the superstructures to three substructures at once, and the structure-soil-structure interaction effect not described in this study will be studied through follow-up studies.

8 REFERENCES

[1] Amin, B. & Majid G. (2019). The role of kinematic interaction on measured seismic response of soil-foundation-structure systems, *Soil Dynamics and Earthquake Engineering*, *125*, 105674 https://doi.org/10.1016/j.soildyn.2019.05.013

[2] Architectural Institute of Korea. (2019). Seismic design criteria for buildings KDS 41 17 00. Korea Construction Standards Center.

[3] Chandra, J. & Gueguen, P. (2019). Nonlinear Response of Soil-Structure Systems using Dynamic Centrifuge Experiments, journal *of Earthquake Engineering*, *23*(10), 1719-1741. https://doi.org/10.1080/13632469.2017.1398692

[4] Deng, Y. H., Dashti, S., Hushmand, A., Davis, C., &

Hushmand, B. (2016). Seismic response of underground reservoir structures in sand: Evaluation of Class-C and C1 numerical simulations using centrifuge experiments, *Soil Dynamics and Earthquake Engineering*, *85*, 202-216. https://doi.org/10.1016/j.soildyn.2016.04.003

[5] European Strong-Motion Database(ESMD, isesd.hi.is

[6] Feifei, S., Lei, X., & Oreste, S. B. (2020). Quantification of seismic mitigation performance of periodic foundations with soil-structure interaction. *Soil Dynamics and Earthquake Engineering*, *132*, 106089. https://doi.org/10.1016/j.soildyn.2020.106089

[7] Federal Emergency Management Agency. (2004-2005). FEMA 440 Improvement of nonlinear static seismic analysis procedures, Washington DC: FEMA.

[8] Federal Emergency Management Agency. (2015). NEHRP Recommended seismic provisions for new buildings and other structures(FEMA P-1050). Building Seismic Safety Council of the National Institute of Building Sciences.

[9] Hamid, A. G. & Reza, A. (2020). A Winkler-based model for inelastic response of soil-structure systems with embedded foundation considering kinematic and inertial interaction effects. *Structures*, *28*, 589-603 https://doi.org/10.1016/j.istruc.2020.09.009

[10] Hushmand, A. (2016). Seismic Performance of Underground Reservoir Structures. *Journal of Geotechnical and Geoenvironmental Engineering*, *142*(7). https://doi.org/10.1061/(ASCE)GT.1943-5606.0001477

[11] Hamid, S. Fatahi, B., & Samali, B. (2013). Lateral seismic response of building frames considering dynamic soil-structure interaction effects. *Structural Engineering and Mechanics*, *45*(3), 311-321. https://doi.org/10.12989/sem.2013.45.3.311

[12] Ko, K. W., Ha, J. G., Park, H. J., & Kim, D. S. (2021). Investigation of period-lengthening ratio for single-degree-of-freedom structures using dynamic centrifuge test. *Journal of Earthquake Engineering*, *25*, 1358-1380. https://doi.org/10.1080/13632469.2019.1576557

[13] Kim, D. K., Kim, H. S., & Kim, J. W. (2022). Seismic Responses of Multi-DOF Structures with Shallow Foundation Using Centrifuge Test. *Earthquake Engineering Society of Korea*, *26*(3), 117-125. https://doi.org/10.5000/EESK.2022.26.3.117

[14] Kim, H. U., Ha, J. G., Kim, D. S., & Joo, K. H. (2017). Overview on Standards for Soil-Structure Interaction Analysis used in Design of Infrastructure. *Earthquake Engineering Society of Korea*, *21*(5), 227-236. https://doi.org/10.5000/EESK.2017.21.5.227

[15] Kim, D. K., Park, H. G., Kim, D. S., & Lee, H. R. (2020). Nonlinear system identification on shallow foundation using Extended Kalman Filter. *Soil Dynamics and Earthquake Engineering*, *125*, 105674. https://doi.org/10.1016/j.soildyn.2019.105857

[16] Lee, S. H., Choo, Y. W., & Kim, D. S. (2013). Performance of an equivalent shear beam (ESB) model container for dynamic geotechnical centrifuge tests. *Soil Dynamics and Earthquake Engineering*, *44*, 102-114. https://doi.org/10.1016/j.soildyn.2012.09.008

[17] Ma, H. & Ma, J. (2018). A Simplified Response Displacement Method for Seismic Calculation of Shallow Buried Structures Using New Load-Structure Model. *IOPConference Series: Earth and Environmental Science*, *186*, 012034. https://doi.org/10.1088/1755-1315/186/2/012034

[18] Paolucci, R., Shirato, M., Yilmaz, M. T. (2007). Seismic behavior of shallow foundations: Shaking table experiments vs numerical modeling. *Earthquake Engineering Structural Dynamics*, *37*(4), 577-595. https://doi.org/10.1002/eqe.773

[19] Penava, D. Kraus, I., Perronijevic, M., & Schmid, G. (2018). Dynamic Soil-Structure Analysis of Tower-Like Structures Using Spectral Elements. *Technical Gazette*, *25*(3), 738-747. https://doi.org/10.17559/TV-20160302114117

[20] Pacific Earthquake Engineering Research Center (PEER), peer.cerkelt.edu.

[21] Sharma, N., Dasgupta, K., & Dey, A. (2020). Natural period of reinforced concrete building frames on pile foundation considering seismic soil-structure interaction effects. *Structures*, *27*, 1594-1612. https://doi.org/10.1016/j.istruc.2020.07.010

[22] Sanket, S. & Prashant, Y. (2020). Effectiveness of friction dampers on seismic response of structure considering soil-structure interaction. *Journal of the Croatian Association of Civil Engineers*, *1*, 33-44. https://doi.org/10.14256/JCE.1982.2017

[23] Tan, H., Wang, D., & Bao, X., Liu, J. (2019). Integral Seismic Deformation Method: A Pseudo-static Method for Seismic Design of Underground Structures. *IOPConference Series: Earth and Environmental Science*, *233*, 032036. https://doi.org/10.1088/1755-1315/233/3/032036

[24] U.S Geological Survey(USGS), earthquake.usgs.gov

[25] Yang, J., Lu, Z., & Li, P. (2020). Large-scale shaking table test on tall buildings with viscous dampersconsidering pile-soil-structure interaction. *Engineering Strucutres*, *220*, 110960. https://doi.org/10.1016/j.engstruct.2020.110960

Contact information

Dong-Kwan KIM, PhD, Assistant Professor
Cheongju University,
Department of Architectural Engineering,
298 Daesung-ro, Cheongju, 28503, Republic of Korea
E- mail: dkkim17@cju.ac.kr

Ho-Soo KIM, PhD, Professor
Cheongju University,
Department of Architectural Engineering,
298 Daesung-ro, Cheongju, 28503, Republic of Korea
E- mail: hskim@cju.ac.kr

Jin-Woo KIM, PhD, Student
(Corresponding author)
Cheongju University,
Department of Architectural Engineering,
298 Daesung-ro, Cheongju, 28503, Republic of Korea
E- mail: wlsdn0907@naver.com

Jin-Young PARK, PhD, Student
Seoul National University,
Department of Architecture and Architectural Engineering,
Gwanak-ro, Gwanak-gu, Seoul, 08826, Republic of Korea
E- mail: wlsdud0902@snu.ac.kr