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Effect on Dynamic Behavior of Group Piles with Changing Thickness of Pile Cap

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ABSTRACT : Instead of a single pile, group piles are usually used for the pile foundation. If the earthquake occurs in the ground where group piles are installed, dynamic behavior of group piles are affected not only by interaction of piles and the ground movement but also by the pile cap. However, in Korea, the pile cap influence is not taken account into the design of group piles. Research on dynamic behavior of group piles has been performed only to verify interaction of piles and the ground and has not considered the pile cap as a factor. In this research, 1g shaking table model tests were performed to verify the thickness of the pile cap affects dynamic behavior of group piles that were installed in the ground where the earthquake would occur. The test results show that, as thickness of the pile cap increased, acceleration and horizontal displacement of the pile cap decreasd while vertical displacement of the pile cap increased. The results also showed that, among the group files tested, acceleration, horizontal displacement, and vertical displacement of the bearing pile are smaller than those of the friction pile.

Keywords : Group piles, Pile cap, Dynamic behavior, Interaction, 1 g shaking table

1. Introduction

If the earthquake occurs in the ground where foundation structures are constructed, dynamic behavior of the ground, foundation structures, and superstructues will be changed by interaction of foundation structures and the ground. Many researchers various model tests to identify dynamic behavior of foundation structures and the ground where the earthquake would occur (Chidichimo et al., 2014; Suzuki et al., 2014, Shirato et al., 2008; Ishizaki et al., 2012). Numerical analysis was also conducted to make a good prediction for model tests (Chau et al., 2009; Taha et al., 2015; Bao et al, 2012).

Among foundation structures, pile foundation, which is deep foundation, is divided into a single pile and a group piles. Usually, a group piles, which are a group of single piles assembled with caps, is used to support superstructures. If the earthquake occurs in the ground where group piles are installed, dynamic behavior of the group piles will be affected not only by interaction of piles and the ground but also by the pile cap.

However, in Korea, the design guidelines for a group piles considers only piles and the ground condition while not considering the pile cap influence (Ministry of Land, Infrastructure and Transport, 2009). Research on dynamic behavior of group piles has been performed to verify only interaction of the pile and ground and has not considered the pile cap (Chidichimo et al., 2014; Suzuki et al., 2014, Shirato et al., 2008; Ishizaki et al., 2012; Chau et al., 2009; Taha et al., 2015; Bao et al., 2012).

In this research, 1 g shaking table model tests were performed to verify the effect of pile-cap thickness on the dynamic behavior of group piles, which are installed in the ground where the earthquake would occur.

2. 1 g shaking table model tests

1 g shaking table model tests were performed with the following test equipment and methods to verify the way thickness of the pile cap affects dynamic behavior of group piles.

2.1 1 g shaking table model test equipment

1 g shaking table model test equipment simulates earth-

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quake shaking by applying cyclic load and earthquake acceleration to the plate. A small scale model structure is built onto the plate where cyclic load and earthquake acceleration are applied to measure displacement and acceleration of the model structure and to identify dynamic behavior of the model structure. With test results of dynamic behavior of the model structure, dynamic behavior of the real structure will be predicted according to scaling laws. Configuration and specification of 1 g shaking table model test equipment are shown in Figure 1 and Table 1.

The model box is used to construct the ground on the plate. The model box is made of 10 layers of a unit 600 mm (B)×600 mm (L)×60 mm (H) by using bearings and elastic springs. This structure helps reflection load to be absorbed at the wall of the model box most effectively because earthquake acceleration generated by the plate occurs on the wall of the model box to impact the ground.

2.2 Materials for the ground and group piles

Standard sand, which is produced in Jumunjin, Korea, and of which particle size is uniform, is used for the model test. Physical properties of standard sand are shown in the Table 2. Bearing piles and friction piles, which are scaled down to 1/40 of the original, following scaling laws, as suggested by Iai (1989), are made for model group piles. As shown in Figure 3, Bearing piles are installed bed rock, but friction piles are not installed bed rock.

Two kinds of pile caps, which were either increased or decreased by 25% of the pile cap as shown in Figure 4, were made to examine the effect of pile-cap thickness on dynamic behavior of group piles. Model group piles consist of hollow pipes and pile cap. Hollow pipes has external 12 mm of diameter and 10 mm of internal diameter, and pile cap is made of cement mortar (K.S. I. 5105) and used as

Table 1. Specification of shaking table model test equipment

Item	Performance
Dynamic load (tonf)	2
Stroke (mm)	±100
Plate (mm)	1000×1000
Frequency (Hz)	0.001～1000
Maximum acceleration (g)	1
Maximum loading load (tonf)	1.0

Table 2. Physical properties of Jumunjin standard sand

Items	Value
Effective grain size, D10 (mm)	0.32
Coefficient of evenness, Cu	1.65
Coefficient of curvature, Cg	1.43
Specific gravity, Gs	2.60
Unified soil classification system (USCS)	SP
Maximum dry unit weight, (kN/m^3)	16.6
Minimum dry unit weight, (kN/m^3)	13.3

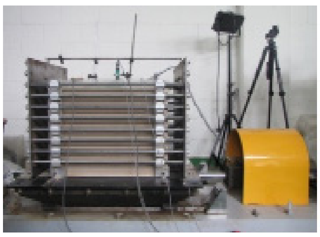
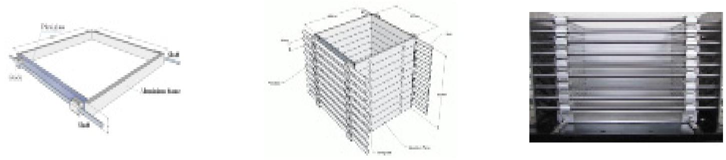
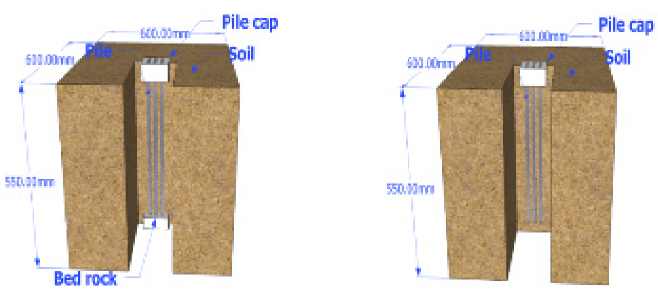


Fig. 1. Shaking table model test equipment



(a) Unit structure (b) Conceptual model box (c) Assembled model box

Fig. 2. Model box



(a) Bearing piles (b) Friction piles

Fig. 3. Sketch of group piles

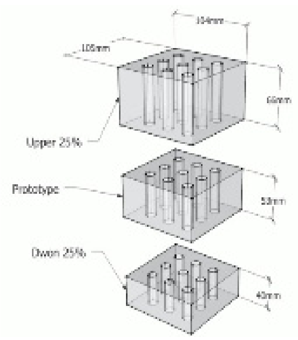


Fig. 4. Pile caps

rigid foundation. Hollow pipes and pile cap are connected by rigid joint.

2.3 Acceleration used for the model test

Group piles used for the model test are bridge substructures of level 1 earthquake-resistance for which the Korean earthquake-resistant design was taken into account. Earthquake acceleration values were selected as the no-collapse level. So, acceleration of the long period and the short period was applied to the model test as shown in Table 3 and Figure 5.

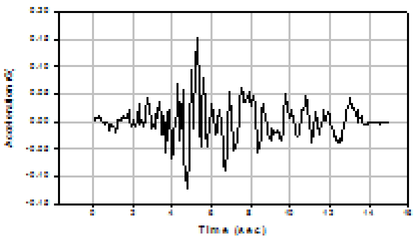
2.4 Model test methods

The model ground was constructed to verify the effect of pile-cap thickness on the dynamic behavior of group piles that are installed in the ground where the earthquake would occur. Jumunjin standard sand was put into the multi-layered calibration chamber to make unit weight and relative density to be 15.0 kN/m^3 and 57% respectively.

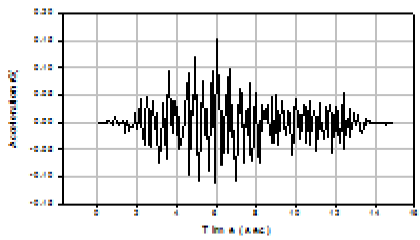
Among group piles installed in the model ground, bearing piles were built into the bottom of the calibration chamber first and then the ground was constructed while friction piles were put into the holes, which were bored to the already-constructed ground. After installation of group piles, pile caps were fixed to the top of group piles to be integrated. It was arranged that the top of pile caps corresponded to the surface of the model ground because embedment depth is not indicated in the design guidelines. Figure 6 shows the group piles installed in the model ground.

An accelerometer and a displacement meter (LVDT, the linear variable differential transformer) were arranged to the top of pile caps as shown in Figure 7, in order to verify the way pile-cap thickness affects the dynamic behavior of group piles. Another accelerometer is arranged on the ground surface to compare the acceleration n measured at the pile cap and the acceleration measured at the ground surface. Then, earthquake acceleration is applied to the model ground to obtain the time history of displacement and acceleration.

Twelve model tests were performed in total as shown in Table 4 to verify the way pile-cap thickness affects the dynamic behavior of group piles.



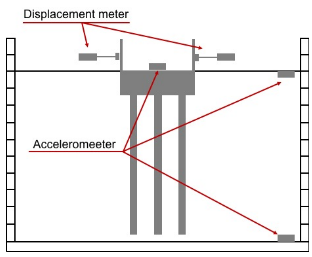
(a) Hachinohe



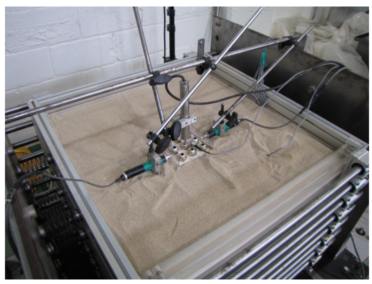
(b) Ofunato

Fig. 5. Time history of acceleration

Fig. 6. Group piles installed in the ground



(a) Location of sensor



(b) Installation of sensors

Fig. 7. Sensors of Location and Installation

Table 3. Specification of acceleration

Types of earthquake	Earthquake occurrence	Magnitude	Maximum acceleration (g)	Characteristics
Hachinohe	Occurred in the Takachin Sea on May 16, 1968	7.8	0.170	Long period
Ofunato	Occured in the Miyagi Sea on June 12, 1978	7.4	0.161	Short period

Table 4. Model test variables

	Bearing piles						Friction piles					
Accele-ration	Hachinohe			Ofunato			Hachinohe			Ofunato		
Pile cap (mm)	40	52.5	65.5	40	52.5	65.5	40	52.5	65.5	40	52.5	65.5
Test #	MBH-1	MBH-2	MBH-3	MBO-1	MBO-2	MBO-3	MFH-1	MFH-2	MFH-2	MF0-1	MF0-2	MF0-3

3. Test result and analysis

1 g shaking table model tests were performed to verify the way pile-cap thickness affects the dynamic behavior of group piles, which were installed in the ground where the earthquake would occur. The test results were converted to the real condition, following scaling laws, for comparison and analysis.

3.1 Acceleration at the pile caps

Acceleration at the caps of group piles, which were installed in the ground where the earthquake would occur, is shown

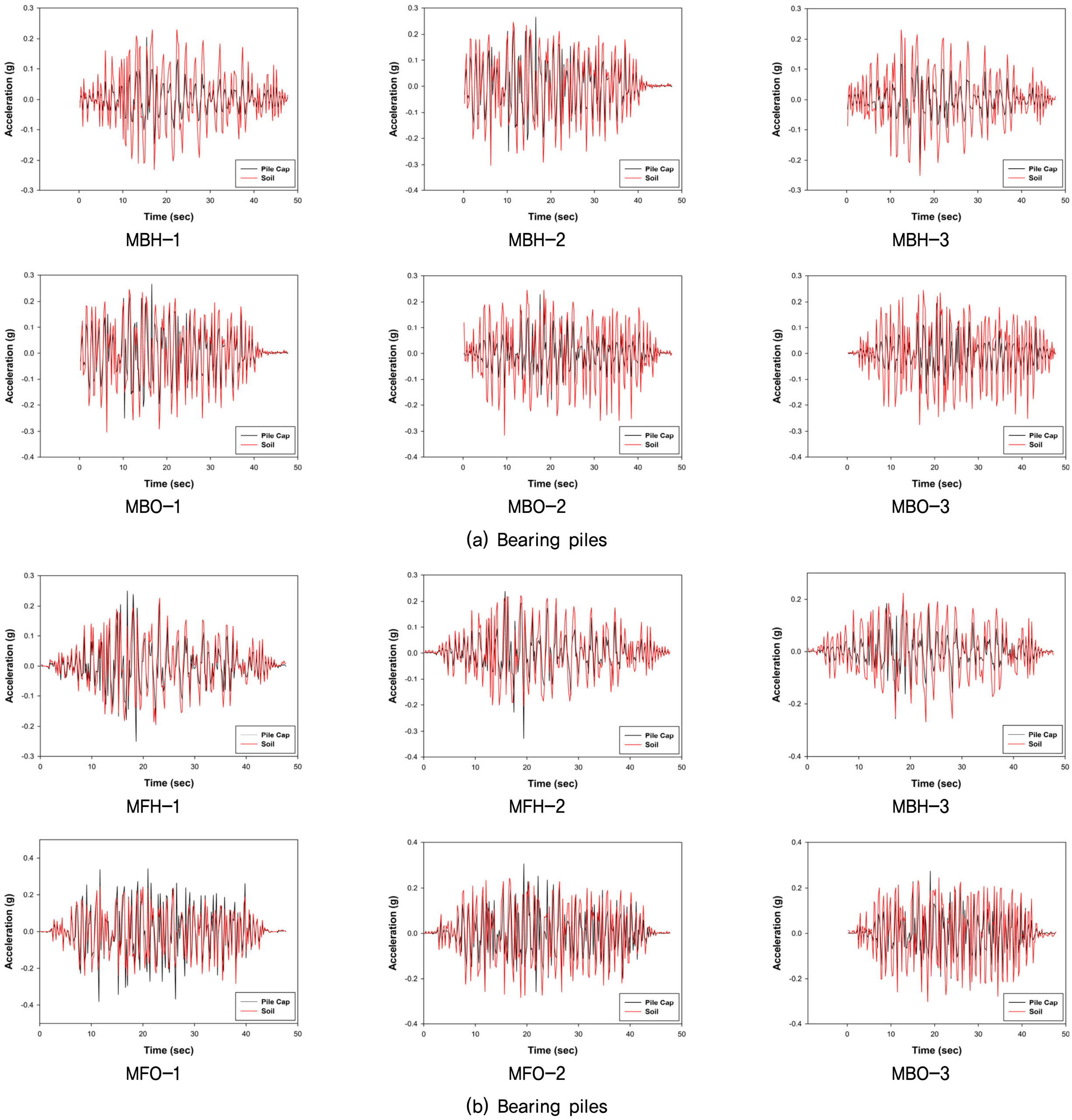


Fig. 8. Spectral acceleration at the top of pile caps and at the ground surface

in Figure 8. Its analysis is shown in Table 5. As thickness of the pile cap increased, acceleration at the pile cap decreased by 4%~26% while acceleration at the ground surface showed little change. However, for the bearing piles, acceleration at the pile cap is 8%~22% smaller than acceleration at the ground surface; for the friction piles, acceleration at the pile cap is 8%~42% bigger than acceleration at the ground surface. It is because bearing piles have more resistance to earthquake acceleration, compared with friction piles. In addition, for acceleration at the pile cap, long-period acceleration response is 10%~26% bigger than short-period acceleration response. It is because the waveform of short period is closer to that of pile cap materials.

3.2 Displacement at the pile caps

Vertical and horizontal displacement at the cap of group piles, which varied according to earthquake load, are shown in Figure 9. Analysis of the result is shown in Table 6. Vertical and horizontal displacement behavior at the cap of both bearing piles and friction piles were similar. However, as thickness of the pile cap increased, vertical displacement increased by 13%~205% while horizontal displacement decreased by 17%~46%. The increase of vertical displacement is because the self weight increased as thickness of the pile cap increased; the decrease of horizontal displacement is because acceleration of the pile cap decreased as thickness of the pile cap increased. Vertical and horizontal displacement at the pile cap were 7%~51% more subject to short-period acceleration than long-period acceleration. It is because the waveform of short period is closer to that of pile cap materials.

4. Conclusion

1 g shaking table model tests were performed to verify the way thickness of the pile cap affects the dynamic behavior of group piles under earthquake load. The test results are as follows.

(1) As the cap thickness of group piles increased, acceleration at the pile cap decreased while horizontal displacement decreased and vertical displacement increased. This result verified that thickness of the pile cap is a factor to affect dynamic behavior of group piles.

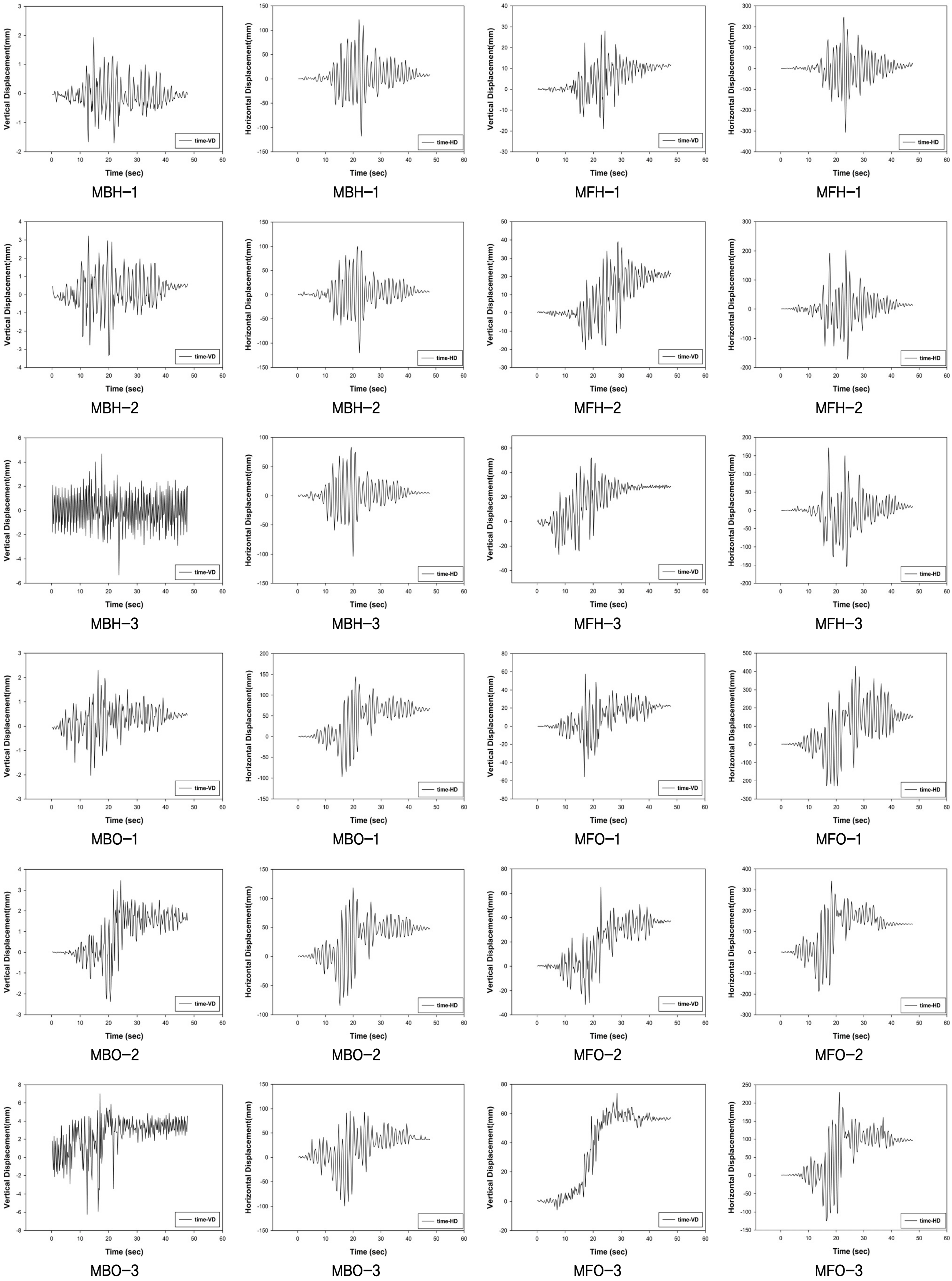
(2) The change of pile-cap thickness will bring about the change of acceleration and horizontal displacement, which will affect dynamic behavior of superstructures. So,

Table 5. Maximum acceleration at the top of pile caps and at the ground surface

	Cap thickness (mm)	Maximum acceleration (g), Max					
		Test #	Long period		Test #	Short period	
			Pile cap	Ground		Pile cap	Ground
Bearing piles	40.00	MBH-1	0.21	0.23	MBO-1	0.27	0.25
	52.50	MBH-2	0.19	0.23	MBO-2	0.23	0.24
	65.50	MBH-3	0.18	0.23	MBO-3	0.20	0.24
Friction piles	40.00	MFH-1	0.25	0.23	MFO-1	0.34	0.24
	52.50	MFH-2	0.24	0.22	MFO-2	0.31	0.24
	65.50	MFH-3	0.22	0.22	MFO-3	0.27	0.25

Table 6. Vertical and horizontal displacement of the pile cap

	Cap thickness (mm)	Test #	Long period wave		Test #	Short period wave	
			Maximum vertical displacement (mm)	Maximum horizontal displacement (mm)		Maximum vertical displacement (mm)	Maximum horizontal displacement (mm)
Bearing piles	40.00	MBH-1	1.94	121.94	MBO-1	2.30	144.54
	52.50	MBH-2	3.22	99.93	MBO-2	3.47	118.24
	65.50	MBH-3	4.96	82.96	MBO-3	7.01	95.37
Friction piles	40.00	MFH-1	28.08	245.90	MFO-1	57.68	428.36
	52.50	MFH-2	39.05	203.02	MFO-2	65.14	342.56
	65.50	MFH-3	52.06	171.70	MFO-3	73.90	229.39



(a) Vertical displacement (b) Horizontal displacement (c) Vertical displacement (d) Horizontal displacement

(A) Bearing piles (B) Friction piles

Fig. 9. Vertical and horizontal displacement of pile caps

thickness of the pile cap should be considered for the earthquake-resistant design of structures.

(3) Acceleration, horizontal displacement, and vertical displacement of bearing piles were bigger than those of friction piles. This result proved that bearing piles are more effectively earth-resistant, compared with friction piles.

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