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ABSTRACT

We carried out centrifuge tests to clarify the seismic behavior of batter-pile foundations. A vertical-pile foundation and a batter-pile foundation without the presence of a superstructure were installed parallel to each other in a soil container filled with dry sand, and were excited simultaneously. Through a comparison of the acceleration and displacement response of the footing, as well as the axial and bending strain of the piles for the two pile foundations, the kinematic response of the seismic behavior of the batter-pile foundation was experimentally investigated.

INTRODUCTION

The lateral stiffness of a pile foundation can be increased by adopting batter piles, which is why they are commonly used in landing piers that are subject to large lateral forces. However, batter piles are seldom used for buildings or civil engineering structures even in the case of large lateral forces. The reasons are as follows:

1) When soil settlement occurs, not only the safety of the pile foundation but also that of the structure as a whole system may be threatened by settlement-induced vertical loads acting on the batter piles.
2) During an earthquake, the piles in a batter-pile foundation may be subject to excessive axial compression and pullout forces, which are not generated in a vertical-pile foundation.
3) The strength of concrete piles is reduced by decreasing the compressive force acting on the piles due to rocking motions induced by the adopted batter piles.
4) Since infinite lateral ground planes cannot be assumed for batter piles, they cannot be expected to have the same horizontal subgrade reaction as that of vertical piles.
5) In urban areas, the use of batter piles is constrained by the boundary lines of adjacent land.

The 1995 Great Hanshin Earthquake in Japan has increased the demand for pile foundations with high seismic performance, as well as lower cost and easier construction. Batter piles can be used with little additional expense, no special design, and hardly any difficulty in construction. Therefore, the seismic behavior of batter piles has recently attracted much research interest, as has research and development related to easy and accurate methods of installing batter piles (Gerolymos, N., et. al., 2008, Giannakou, A., et. al., 2007, Poulos., N., 2006).

In this study, we carried out centrifuge shaking table tests to clarify the seismic behavior of batter-pile foundations. A vertical-pile foundation and a batter-pile foundation were installed parallel to each other in a soil container filled with dry sand, and were excited simultaneously (Tazoh, T., et. al., 2005, Tazoh, T., et. al., 2007). As our objective was to investigate the fundamental characteristics of the seismic behavior of batter piles, none of the pile-foundation models had a superstructure. This study focused on the kinematic interaction of batter piles (Fan, K., et. al., 1991, Mylonakis, G., et. al., 1997, Mylonakis, G., 2001, Nikolaou, S., et. al., 2001, Sica, S., et., al., 2007, Tazoh, T., et. al., 1987). Through a comparison of the acceleration and displacement response of the footing, as well as the axial and bending strain of the piles for the two pile foundations, the kinematic nature of the seismic behavior of the batter-pile foundation was experimentally studied.

CENTRIFUGE TESTS

The most direct and effective way to quantitatively and qualitatively investigate the seismic behavior of batter piles is to compare the seismic behavior between a vertical-pile foundation and a batter-pile foundation under the same input motions. Each test for each model must be carried out under nearly identical conditions with respect to input motions, soil conditions, and soil behavior. Note, however, that it is impossible to achieve complete similarity between shaking table tests due to the difficulty of reproducing the input motion and nonlinear behavior of the soil.

Therefore, a vertical-pile foundation and a batter-pile foundation without the presence of a superstructure were installed parallel to each other in a soil container, as shown in Figure 1, and were excited simultaneously.
A laminar box was used as the soil container to allow shear deformation of the soil deposit as in the free field. Actually, installing two models that behave differently in a laminar box

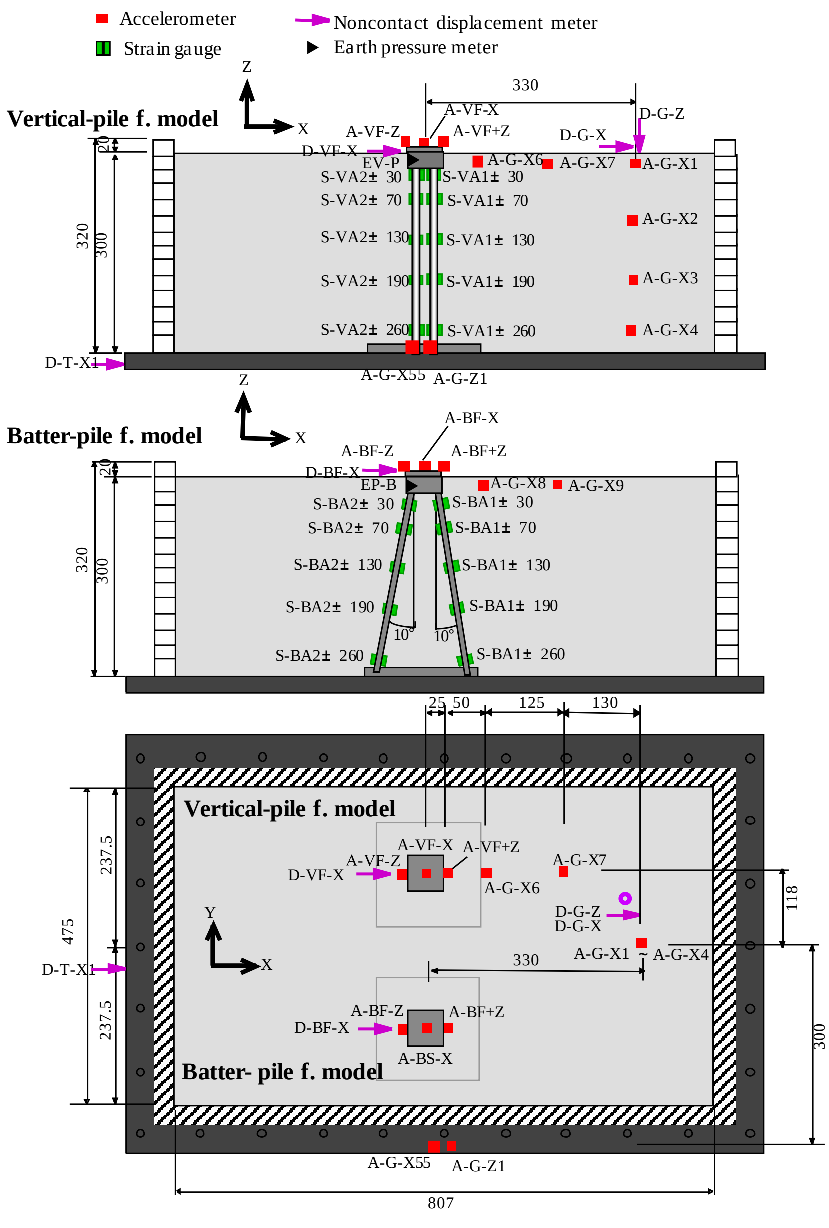


Figure 1 Longitudinal sections and plan of the 1/30-scale centrifuge model
(Scale unit: mm, for the prototype dimensions: multiply by 30. A vertical-pile foundation and a batter-pile foundation without the presence of a superstructure were set parallel to each other in a soil container which was filled with dry sand, and were excited simultaneously.)

Table 1 Scaling ratios of the testing model

Item		Symbol	Unit	Centrifuge model	Prototype	Scale
Sand stratum	Depth	H	m	0.3	9	1/N
	Density	ρ_t	KN/m^3	15.0	15.0	1
Structure	Width	W	m	0.05	1.5	1/N
	Height	H	m	0.04	1.2	1/N
	Mass	M	kg	0.785	21,195	1/N^3
Footing	Width	W	m	0.05	1.5	1/N
	Height	H	m	0.03	0.9	1/N
	Mass	M	kg	0.58875	15,896	1/N^3
Column	Width	L	m	0.006	0.18	1/N
	Width (shaking direction)	W	m	0.004	0.12	1/N
	Moment of inertia of area	I	m^4	3.20E-11	2.59E-05	1/N^4
	Length	L	m	0.06	1.8	1/N
Pile	Diameter	D	m	0.01	0.3	1/N
	Thickness	t	m	0.0002	0.006	1/N
	Young's modulus	E	MN/m^2	2.06E+05	2.06E+05	1
	Area	A	m^2	6.16E-06	5.54E-03	1/N^2
	Moment of inertia of area	I	m^4	7.40E-11	5.99E-05	1/N^4
	Normal stiffness	EA	MN	1.27E+00	1.14E+03	1/N^2
	Bending stiffness	EI	MN-cm^2	1.52E-09	1.23E-03	1/N^4
Acceleration	Centrifuge	*g*	*g*	30	1	N
	Earthquake	α	Gal	6000	200	N
Other parameters	Displacement	δ	m	1	30	1/N
	Force	F	N	1	900	1/N^2
	Stress	τ	kPa	1	1	1
	Strain	γ		1x10^{-6}	1x10^{-6}	1
	Time	t	s	1	30	1/N
	Frequency	f	Hz	30	1	N

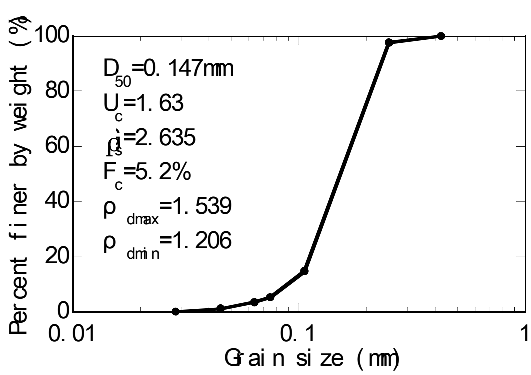


Figure 2 Grain size accumulation curve of silica sand No. 7
(Mean particle diameter D_{50} = 0.15 mm, Soil density ρ_s = 2.635 g/cm^3,
Maximum dry density ρ_{max} = 1.539 g/cm^3, Minimum dray density ρ_{min} = 1.206 g/cm^3)

is not an appropriate testing method because the behavior of the models might influence each other. However, considering the inconsistency of the input motion and the difficulty of reproducing the soil conditions and nonlinearity, we believe that this method is more reasonable than individually testing the vertical-pile foundation and batter-pile foundation separately.

The interior of the soil container is 805 mm in length, 474 mm in width, and 324 mm in height. All tests were conducted at centrifugal acceleration of 30 g on a 1/30-scale model. Table 1 shows the scaling ratios of the models.

The vertical-pile foundation and the batter-pile foundation each have four piles, and the pile heads and pile tips are rigidly connected to the footing and the base of the soil container, respectively. The batter piles are identically inclined at a 10° angle. The soil deposit is a uniform layer consisting of dry silica sand No. 7 (Mean particle diameter D_{50} = 0.15 mm; Soil density ρ_s = 2.635 g/cm^3; Maximum dry density ρ_{max} = 1.539 g/cm^3; Minimum dry density ρ_{min} = 1.206 g/cm^3). Thickness and relative density of the soil deposit is 300 mm (prototype: 9 m) and Dr = 60%, respectively.

Figure 2 shows the grain size accumulation curve of silica sand No. 7. Table 2 shows the materials and size of the experimental model used in the tests and Photograph 1 shows the test model. Sixty-two monitoring channels in total were installed, with the sensors comprising seventeen accelerometers, five non-contact displacement meters, and forty strain gauges (Table 3). The test was conducted a total of nine times, varying the input motion and maximum acceleration as shown in Table 4.

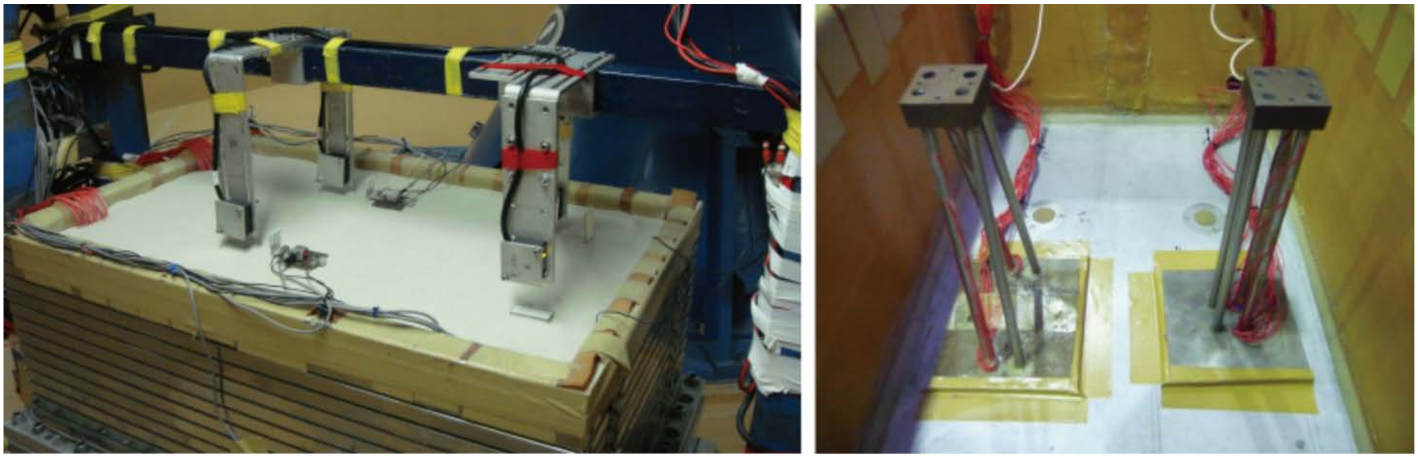
While the purpose of this study was to clarify the kinematic interaction of the batter piles, consideration must also be given to effects from the mass of the footing (made of steel, size: 3×5×5 cm). The inertial interaction caused by the inertial force of the footing might be included in the results, which consequently may not represent the perfect kinematic interaction.

Table 2 Materials and dimensions of the test model

Parts	Material & size
Laminar box	805mm, 475mm, 324mm（Inner size: length, width, depth）
Soil deposit	Dry sand: Silica No.7（Dr ＝ 60%）， Thickness: 300 mm
Vertical pile	Stainless steel No. of piles：4 (2×2) , Inclination angle: 0° Length: 270 mm，Diameter:10 mm，Thickness: 0.2 mm
Batter pile	Stainless steel No. of piles：4 (2×2) , Inclination angle: 10° Length: 274 mm，Diameter: 10 mm，Thickness: 0.2 mm
Footing	Steel Thickness: 30 mm，Plan size: 50 mm×50 mm

Table 3 Installed sensors
(62 monitoring channels were installed, with the sensors comprising 17 accelerometers, 5 non-contact displacement meters, and 40 strain gauges.)

Transducer	Location	Direction	Number	Subtotal	Total
Accelerometer	Batter pile	X	2	17	62
		Z	2		
	Vertical pile	X	2		
		Z	2		
	Ground	X	6		
	Base	X	1		
	Table control	X	1		
	Centrifugal acc.	Z	1		
Non-contact displacement meter	Batter pile	X	1	5	
	Vertical pile	X	1		
	Ground	X	1		
		Z	1		
	Base	X	1		
Strain gauge	Batter pile	Pile-BA1	10	40	
		Pile-BA2	10		
	Vertical pile	Pile-VA1	10		
		Pile-VA2	10		



Photograph 1 Testing Model
(The pile foundations have four piles.)

Table 4 Test cases

Input Motion	Freq. of input motion (Hz)	Max. acc. of input motion (Gal)	Test case No.
Sweep test motion	1.7-10 Hz	5	1-1
		15	1-2
		30	1-3
Sinusoidal excitation	3.5 Hz	50	2-1
		100	2-2
		200	2-3
El Centro record	El Centro record N-S component	50	3-1
		100	3-2
		200	3-3

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Figure 3 shows the frequency transfer function calculated by the acceleration records between the soil surface and the input motion of the sweep test. The predominant frequency of the ground is 3.5 Hz in the case of maximum acceleration of input motion at 5 Gal. The predominant frequencies are 3.2–3.3 Hz and 3.0–3.1 Hz, and also the peak acceleration amplification factors decrease corresponding to the increase in maximum acceleration of the input motion to 15 Gal and 30 Gal.

Figure 4 shows the frequency transfer function between the ground surface and input motion obtained from El Centro record excitation. The predominant frequency of the ground is 3.4 Hz in the case of maximum acceleration of input motion at 50 Gal. The predominant frequencies are 2.8–2.9 Hz and 2.4–2.5 Hz, and also the peak acceleration amplification factors decrease according to the increase in maximum acceleration of the input motion to 100 Gal and 200 Gal. These phenomena were obviously produced by the nonlinearity of the soil.

Figure 5 shows the relationship between horizontal displacement and rotational angle of the footing based on the data from sinusoidal excitation of 3.5 Hz, in order to investigate the rotational characteristics of the footing of the vertical-pile foundation and the batter-pile foundation. The rotational angle is calculated by dividing the difference in the vertical displacement based on the data of the accelerometers installed at both sides of the footing by the distance between the two accelerometers.

The fact that there is no phase difference between the sway and the rocking motion indicates that the response of the footing to motion to the right is counterclockwise rotation, as shown in Figure 7. There is no phase difference between the sway and the rocking motion of the vertical-pile foundation; on the other hand, anti-phase behavior can be seen in the data for the batter-pile foundation.

Figure 6 shows the data obtained from El Centro record excitation at the maximum acceleration of 200 Gal. The same trend as seen in the case of sinusoidal excitation can also be found in Figure 6. The phenomena of the opposite phase between the sway and the rocking motions of the vertical-pile foundation and the batter-pile foundation can be found in all of the other test data. From Figures 5 and 6, it can also be seen that the rotation angles of the batter-pile foundation are almost two times larger than those of the vertical-pile foundation.

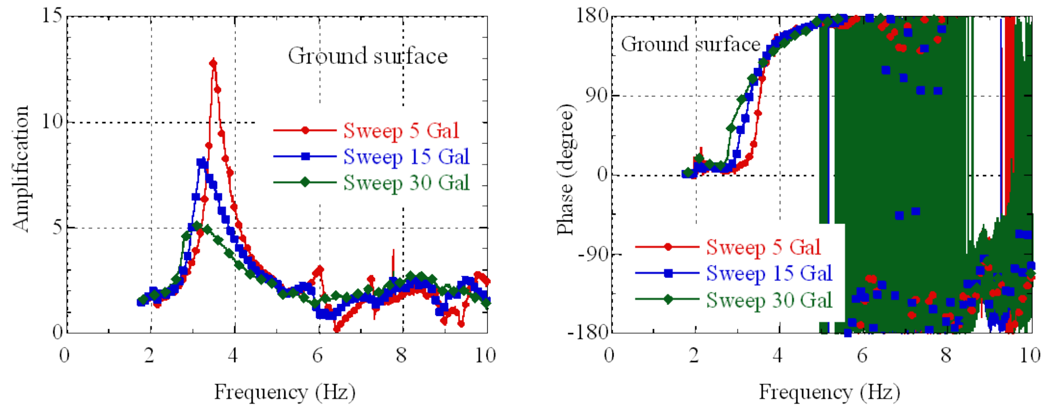


Figure 3 Frequency transfer function of the ground surface obtained from sweep test
(5 Gal, 15 Gal, 30 Gal)

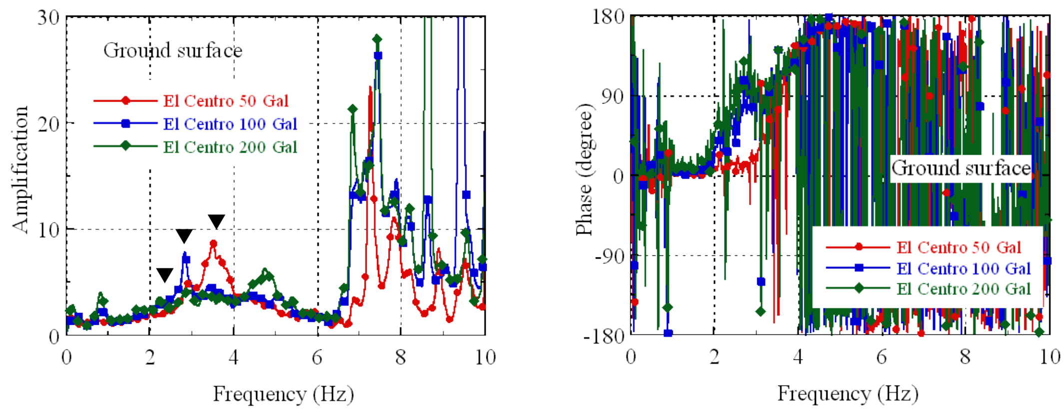


Figure 4 Frequency transfer function of the ground surface obtained from the El Centro record excitations
(50 Gal, 100 Gal, 200 Gal)

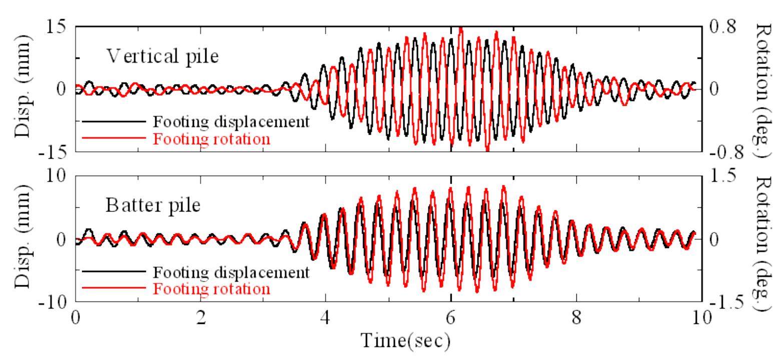


Figure 5 Comparisons of horizontal displacement and rotational angle of the footings between the vertical-pile foundation and the batter-pile foundation (Sinusoidal excitation: 3.5 Hz, 200 Gal)

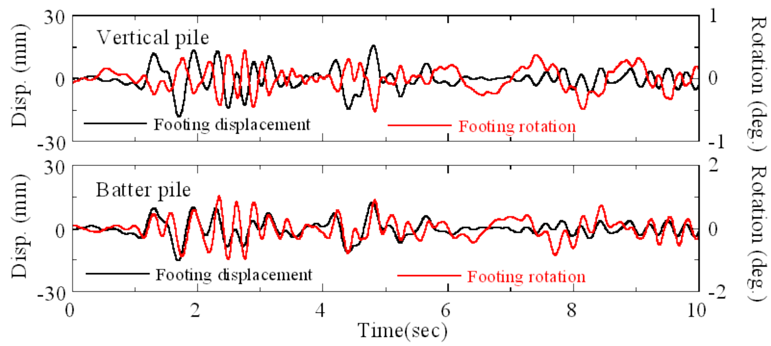


Figure 6 Comparisons of horizontal displacement and rotational angle of the footings between the vertical-pile foundation and the batter-pile foundation (El Centro record: 200 Gal)

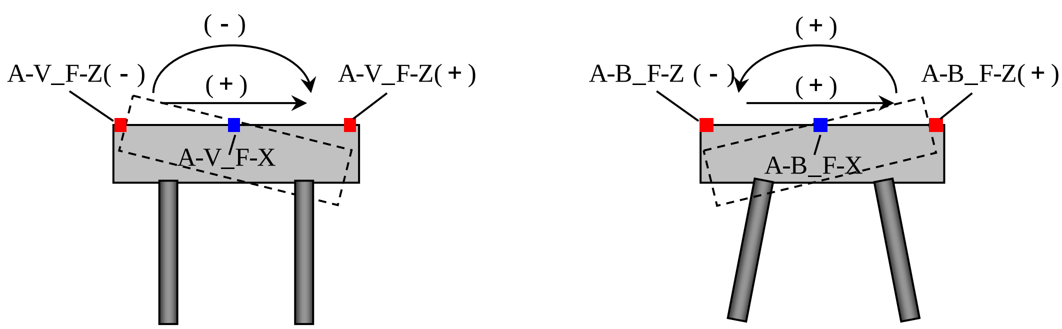


Figure 7 Kinematic responses of footings

Figure 8 shows the maximum-value distribution of the bending and axial strains of the piles in the vertical-pile foundation (pile-VA1) and the batter-pile foundation (pile-BA1) obtained from sinusoidal excitation of 3.5 Hz. The frequency of 3.5 Hz closely corresponds to that of the predominant frequency of the ground as shown in Figure 3. The largest values were obtained at the pile heads, and the bending and axial strains of the batter-pile foundation are larger than those of the vertical-pile foundation in all cases, as shown in Figure 8.

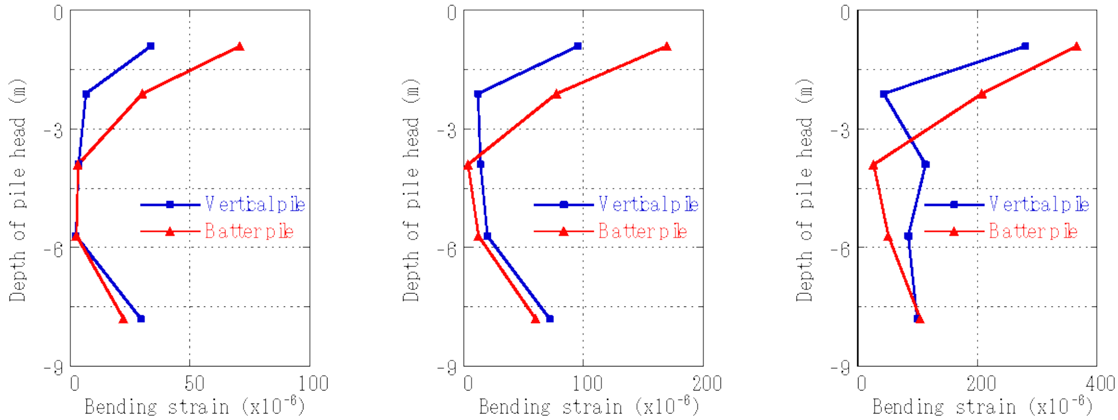
Figure 9 shows the maximum-value distribution of the bending and axial strains of the piles in the vertical-pile foundation (pile-VA1) and the batter-pile foundation (pile-BA1) obtained from El Centro record excitation. The largest values were obtained at the pile heads, and the bending and axial strains of the batter-pile foundation are larger than those of the vertical-pile foundation, likely due to the sinusoidal excitation.

Figures 10 and 11 show the maximum values for acceleration of the footings and the ground surface, and the bending and axial strains at the pile heads corresponding to the increments in maximum acceleration of the input motion. From the figures, it can be seen that the maximum acceleration of the footing of the vertical-pile foundation is larger than that of the batter-pile foundation and that both the bending and axial pile strain of the batter-pile foundation are larger than those of the vertical-pile foundation in both the sinusoidal and El Centro record excitation.

ASEISMICITY OF BATTER PILE

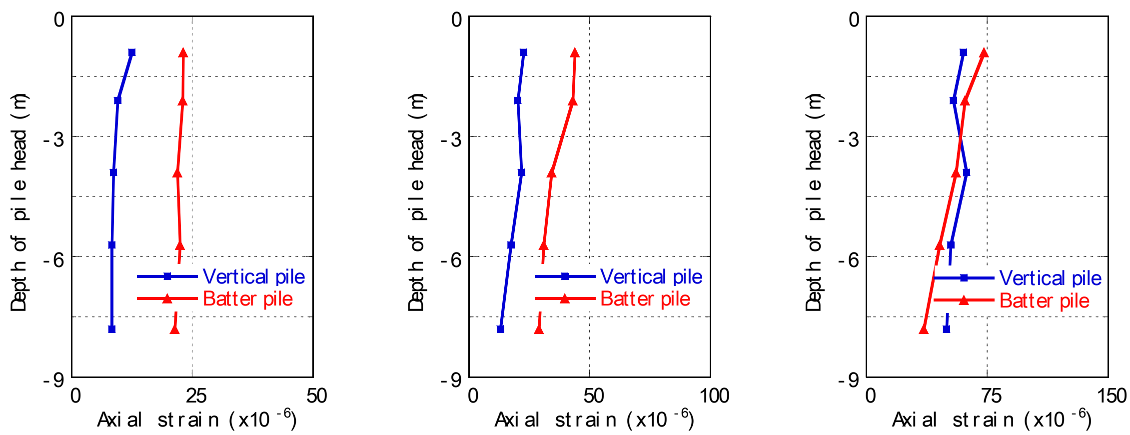
Figures 12 and 13 compare the frequency transfer functions of the horizontal acceleration of the footing and input motion between the vertical-pile foundation and the batter-pile foundation obtained from sweep test and El Centro record excitation. The difference between the frequency transfer functions of the two pile foundations represents the aseismicity of the batter-pile foundation. From these figures, it can be elucidated that the batter-pile foundation has a certain level of aseismicity in all of the frequency ranges.

Figures 14 and 15 compare the frequency transfer functions of the bending and axial strains of the piles and input motion between the vertical-pile foundation and the batter-pile foundation calculated using the data from the sweep test and El Centro record excitation. From these figures, it can be seen that the strain of the batter piles is larger than that of the vertical piles. Therefore, it is considered that the compensation for the aseismicity of batter piles seeks large cross-sectional efficiency for the batter piles.



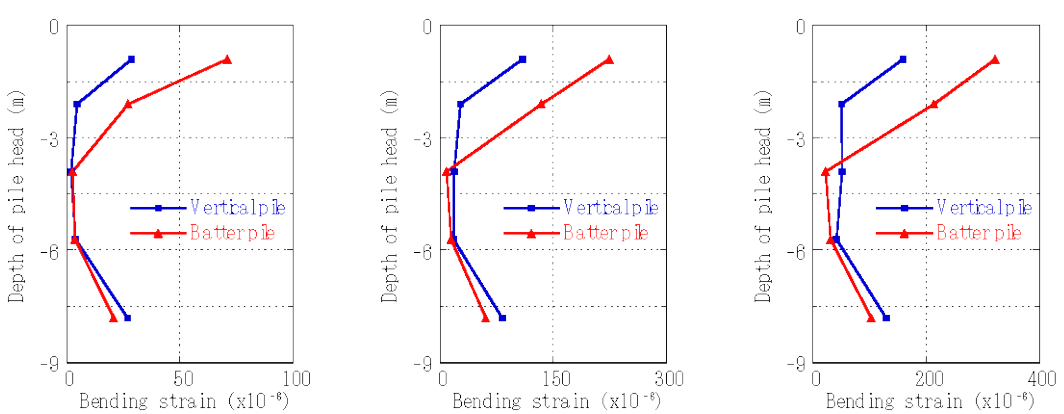
(a) 50 Gal (b) 100 Gal (c) 200 Gal

Figure 8.1 Bending strain distributions of the vertical-pile foundation (pile-VA1) and the batter-pile foundation (pile-BA1) obtained from the sinusoidal excitation of 3.5 Hz (50 Gal, 100 Gal, 200 Gal)



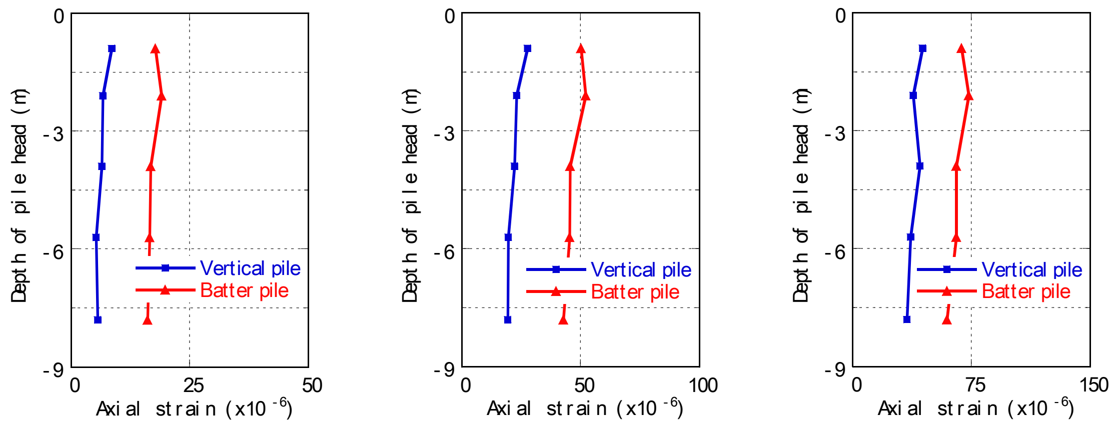
(a) 50 Gal (b) 100 Gal (c) 200 Gal

Figure 8.2 Axial strain distributions of the vertical-pile foundation (pile-VA1) and the batter-pile foundation (pile-BA1) obtained from the sinusoidal excitation of 3.5 Hz (50 Gal, 100 Gal, 200 Gal)



(a) 50 Gal (b) 100 Gal (c) 200 Gal

Figure 9.1 Bending strain distributions of the vertical-pile foundation (pile-VA1) and the batter-pile foundation (pile-BA1) obtained from El Centro record (50 Gal, 100 Gal, 200 Gal)



(a) 50 Gal (b) 100 Gal (c) 200 Gal

Figure 9.2 Axial strains distributions of the vertical-pile foundation (pile-VA1) and the batter-pile foundation (pile-BA1) obtained from El Centro record (50 Gal, 100 Gal, 200 Gal)

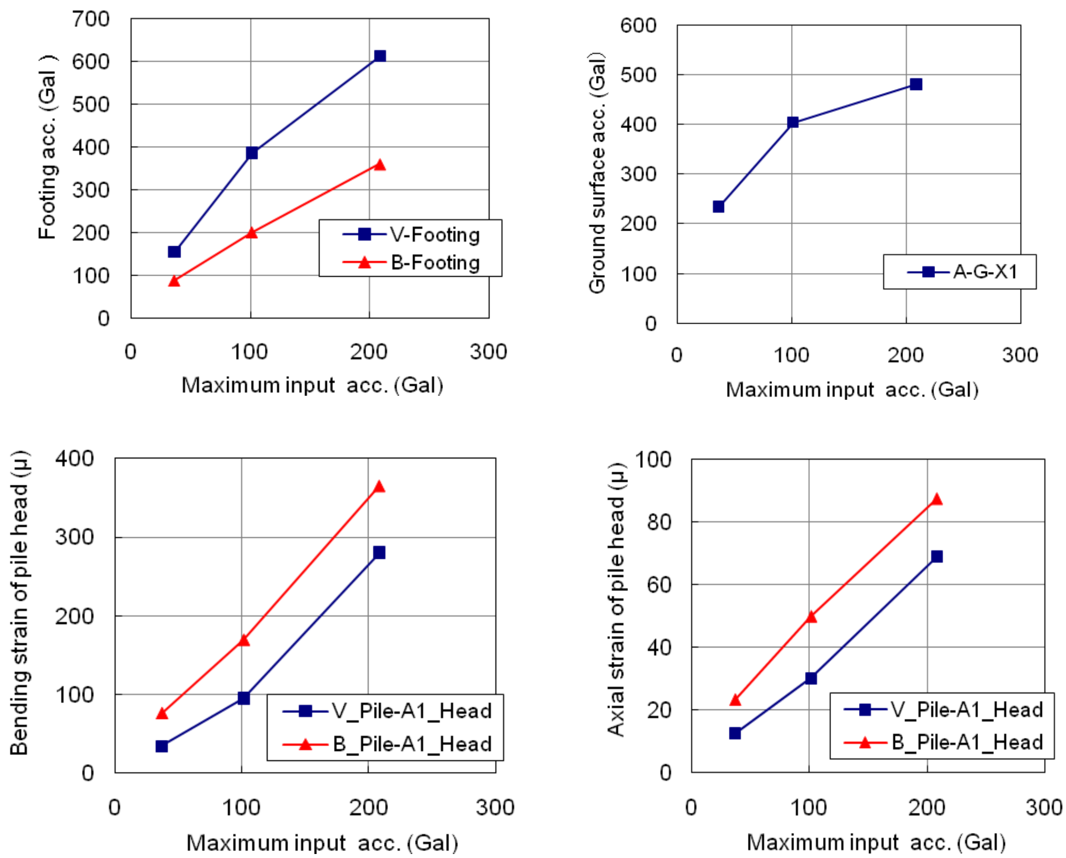


Figure 10 Maximum values of the accelerations of the footings and the ground surfaces, and the bending and axial strains at the pile-heads (Sinusoidal excitation: 3.5 Hz)

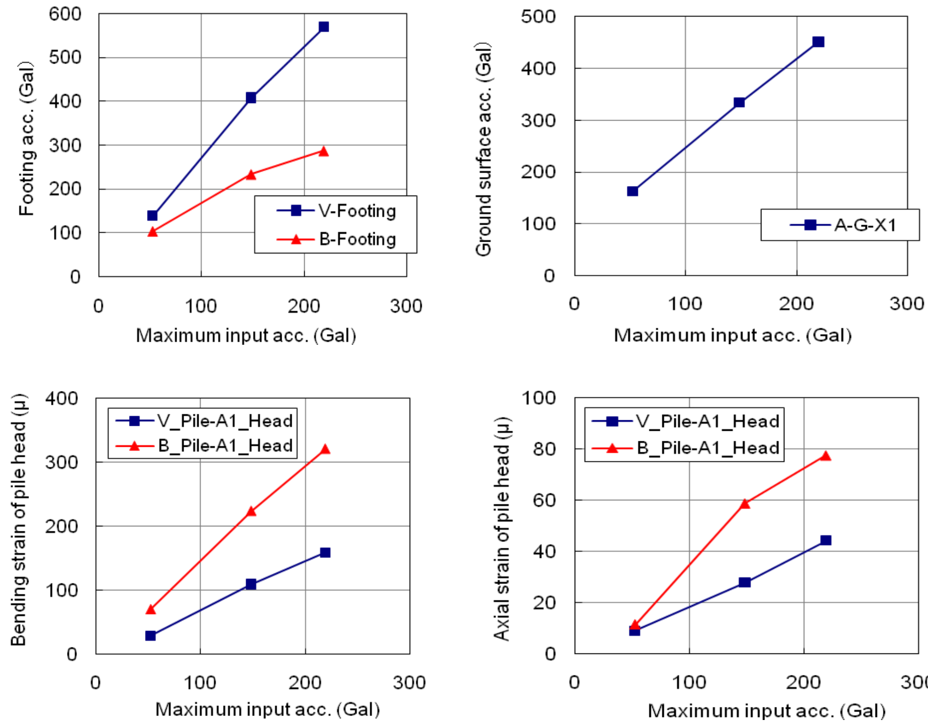
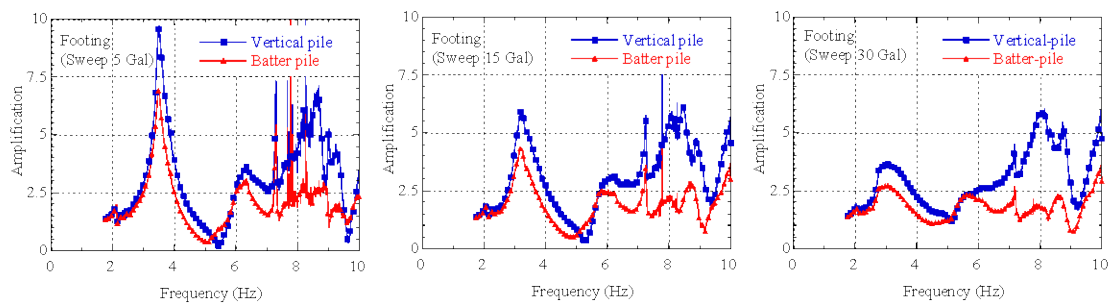
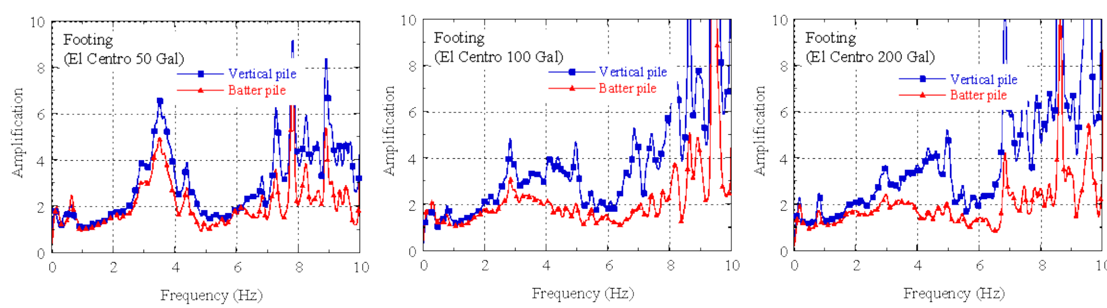


Figure 11 Maximum values of the accelerations of the footings and the ground surfaces, and the bending and axial strains at the pile-heads (El Centro record)



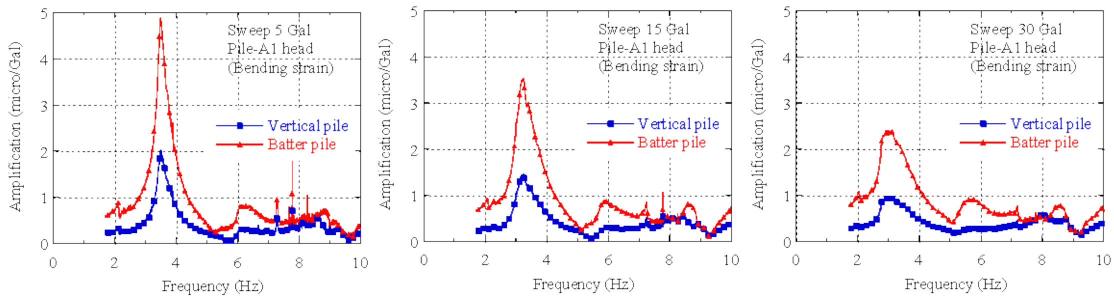
(a) 50 Gal (b) 100 Gal (c) 200 Gal

Figure 12 Aseismicity of the batter-pile foundation: Comparison of the frequency transfer function between the horizontal acceleration of the footing and input motion in the vertical-pile foundation and the batter-pile foundation obtained from sweep tests (5 Gal, 15 Gal, 30 Gal)

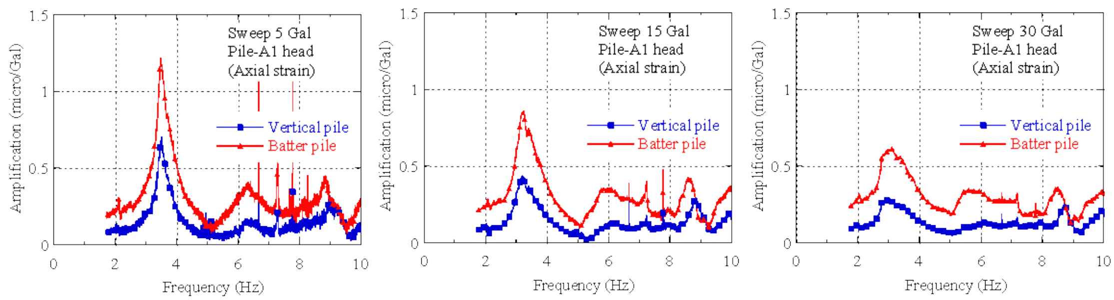


(a) 50 Gal (b) 100 Gal (c) 200 Gal

Figure 13 Aseismicity of the batter-pile foundation: Comparison of the frequency transfer function between the horizontal acceleration of the footing and input motion in the vertical-pile foundation and the batter-pile foundation obtained from El Centro record (50 Gal, 100 Gal, 200 Gal)

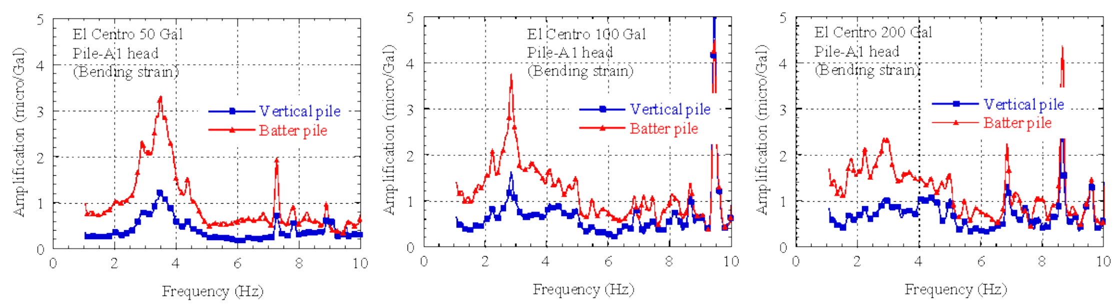


(a) Bending strains

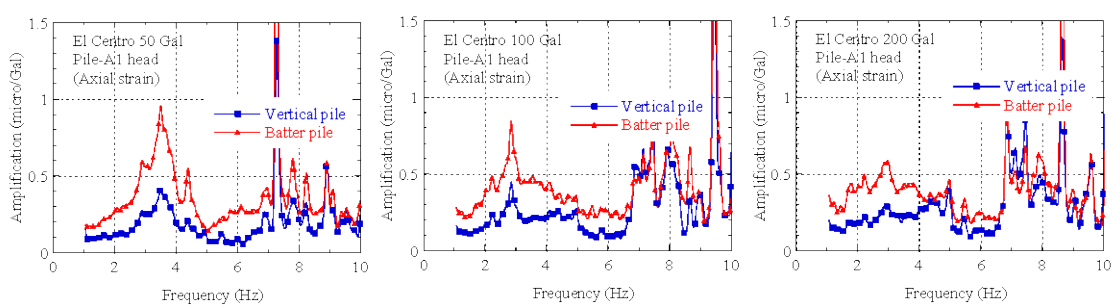


(b) Axial strains

Figure 14 Comparisons of the frequency transfer functions of the bending and axial strains of the piles and input motion between the vertical-pile foundation and the batter-pile foundation (sweep tests)



(a) Bending strains



(b) Axial strains

Figure 15 Comparisons of the frequency transfer functions of the bending and axial strains of the piles and input motion between the vertical-pile foundation and the batter-pile foundation (El Centro record)

CONCLUSIONS

The main conclusions of the study are as follows:

1) The response of the footing of the vertical-pile foundation to motion to the right is counterclockwise rotation. On the other hand, that of the batter-pile foundation is rotation in the opposite direction to that of the vertical-pile foundation.
2) Bending and axial strains attain the largest values at the pile heads in both the vertical-pile foundation and batter-pile foundation.
3) Improved aseismicity by adopting batter piles can be gained in almost all frequency ranges.
4) Bending and axial strains of the batter-pile foundation are larger than those of the vertical-pile foundation. In other words, the compensation for the aseismicity of batter piles seeks large cross-sectional efficiency for the batter piles.

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