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Dynamic Behaviors of Batter Piles and Countermeasures to Improve Their Seismic Performance Using Shaking Table Tests

진동대 모형실험을 이용한 경사말뚝의 동적 거동 분석과 내진성능 향상을 위한 보강기법 개발

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요 지

본 연구에서는 경사말뚝과 수직말뚝의 정적/동적 거동을 분석하고, 경사말뚝의 내진성능을 향상시키기 위한 보강방법을 제안하기 위하여 진동대 모형시험을 수행하였다. 첫 번째로 정적 횡방향 재하시험을 수행하여 정적 횡방향 하중을 받는 경사말뚝과 수직말뚝의 거동을 비교·분석하였으며, 두 번째로 진동대 모형실험을 수행하여 말뚝머리에서 발생하는 축력과 휨모멘트를 분석하여 지진하중에 대한 경사말뚝의 취약성을 확인하였다. 마지막으로 지진시 경사말뚝의 내진성능을 향상시킬 수 있는 보강기법을 제안하고 진동대 모형실험을 통하여 그 유효성을 확인하였다. 본 연구에서 경사말뚝의 내진보강기법으로 말뚝머리와 상부갑판을 연결할 때 고정연결 대신 연성이 큰 고무와 힌지를 이용한 연결조건을 제안하였으며, 경사말뚝의 경사각이 수직 대 수평비가 8:3 일 때 지진하중에 의해 경사말뚝에서 최소의 부재력이 발생하는 것을 확인하였다.

Abstract

Shaking table tests are performed to investigate the seismic behavior of the batter pile and to bring up the countermeasures to improve the seismic performance of the batter pile. First of all, this study demonstrates how batter piles and vertical piles behave under static lateral loadings. Secondly, the vulnerability of batter plies under dynamic lateral loadings is demonstrated showing the axial forces and bending moments mobilized at the pile heads during shaking table tests. Thirdly, countermeasures to overcome the vulnerability of batter piles during earthquakes are pursued. The countermeasures investigated in this study include introduction of a rubber element at the pile head and the deck plate connection, and introduction of hinge connection. Finally, the slope of batter piles which induces the minimum pile forces during the dynamic loadings are investigated and found to be 8:3 (Vertical to Horizontal).

Keywords : Batter pile, Countermeasures against earthquake, Dynamic loading, Shaking table test, Soil-pile interaction

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1. Introduction

When structures are constructed on soft soils, group piles are used to support the structures with their construction ability, economical efficiency, and large bearing capacity. Also, when group piles are subjected to large lateral loads, both batter piles and vertical piles are used in the group piles (Bowles, 1997; Erickson et al., 1998). However, while batter piles show high resistance against the static lateral loads they show a poor performance under seismic loadings (Erickson et al., 1998). This weakness may be the development of excessive axial forces at their heads due to the dynamic lateral loads caused by such phenomena as earthquakes. Therefore, vertical piles are preferred to batter piles in high seismicity areas (Erickson et al., 1998). However, there are few researches about how batter piles behave under dynamic loadings and how to improve seismic performance of batter piles.

The purposes of this study are as followings: first, this study demonstrates how batter piles and vertical piles behave under static lateral loadings. Secondly, the vulnerability of batter plies under dynamic lateral loadings is demonstrated. Thirdly, countermeasures to improve the poor seismic performance of batter piles during earthquakes are proposed.

2. Model Tests

Shaking table model tests are performed to investigate the behaviors of the vertical and batter piles. Figure 1 shows the schematic diagram of model test setup. Dimension (L×B×H) of the soil container made of acrylic plates is 150 cm × 100 cm × 70 cm. Model piles are 3×3 group pile, and 700 mm in length, 17 mm in outer diameter, and 1 mm in thickness. Young's modulus and moment of inertia of model piles are 70 GPa and 1608.5 mm^4, respectively. The pile spacing is 6D (D=outer diameter of model pile). Figure 2 shows pile arrangement and pile numbering, and pile No. 4 in row of batter piles is analyzed. The deck plate is made of steel plate, whose dimension is 300 mm in length, 300 mm in width, and 10 mm in thickness. Jumoonjin sands are placed in the soil container for the model ground soils where water is not considered. The effective grain size and uniformity coefficient of Jumoonjin sands are 0.4 mm and 1.53, respectively. The relative density (D_r) of the model deposit is 70%, which is compacted by vibration for 4 minutes using sinusoidal wave, 20 Hz in frequency and 0.4 g in magnitude. The maximum and minimum dry unit weights of Jumoonjin sand are 16.27 kN/m^3 and 13.03 kN/m^3, respectively. The Sinusoidal waves and historical earthquakes, El Centro earthquake and Hachinohe earthquake are used as input motion. In the tests, El Centro earthquake which has been widely used as a standard strong ground motion and Hachinohe earthquake which has been used in earthquake resistant design of ports and harbor geostructures in Korea and Japan are used to avoid the effects of frequency on the dynamic behaviors of pile systems. For the purpose of this study, we execute the following model tests; (a) Static lateral load tests, (b) Impact load tests, and (c) Shaking table tests. Static lateral load tests

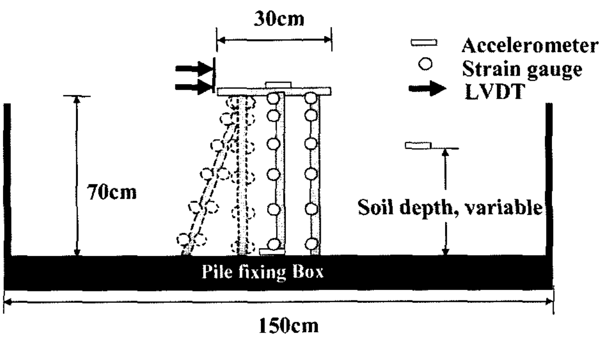


Fig. 1. Schematic diagram of model test setup

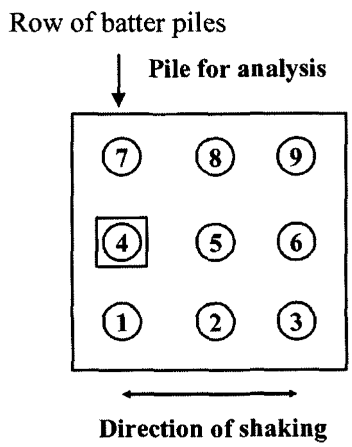
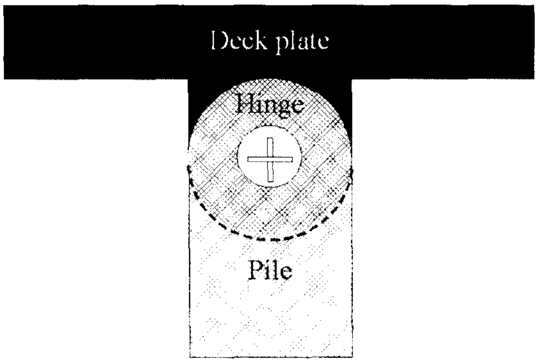
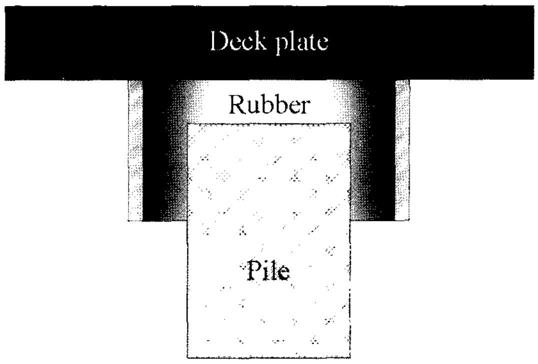


Fig. 2. Pile arrangement and numbering



(a) Hinge connection



(b) Rubber connection

Fig. 3. Pile head connections to improve the seismic performance of batter piles

are performed to obtain the static lateral stiffness of a model pile system, and the natural frequency of the model pile system is evaluated by analyzing the data from impact load tests. And shaking table tests are performed to analyze dynamic behaviors of vertical and batter piles, and verify the effectiveness of countermeasures for improving a poor seismic performance of batter piles.

In this study, the countermeasures for improving the seismic performance of batter piles during earthquakes include modification of pile head connections, as shown in Figure 3, and investigation of the slope of batter piles in which member forces of batter piles are generated in minimum during the dynamic loadings.

3. Test Results

3.1 Comparison of Batter Pile and Vertical Pile Behaviors

Static lateral load tests are conducted with increasing the soil depth by 0, 18, 36, and 54 cm and connecting the pile heads to the deck plate by fixed condition for the purpose of comparison of static behaviors between the batter piles and vertical piles. Pile No. 4 in Figure 2 is analyzed in this study.

Figure 4 shows the static lateral load-displacement curves of the batter and vertical piles when the soil depth is 36 cm. As shown, the initial lateral stiffness of the batter pile is larger than that of vertical one. Figure 5 shows the initial lateral stiffness ratios varying with the embedded depth ratios of piles, where the initial lateral stiffness ratio is defined by initial lateral stiffness of batter piles over that of vertical piles and the embedded depth ratio of piles the embedded depth over the whole pile length. As the embedded depth ratio of piles increases, the initial lateral stiffness ratio decreases. And the initial lateral stiffness of batter pile is always larger than that of vertical pile. From these results, it was confirmed that batter piles are more effective than vertical piles for static lateral loading.

Figure 6 shows the maximum values of moment, shear

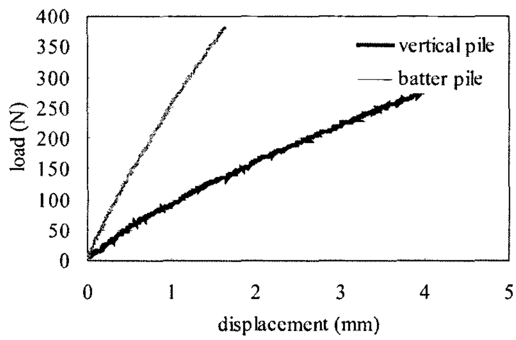


Fig. 4. Static load-displacement curve

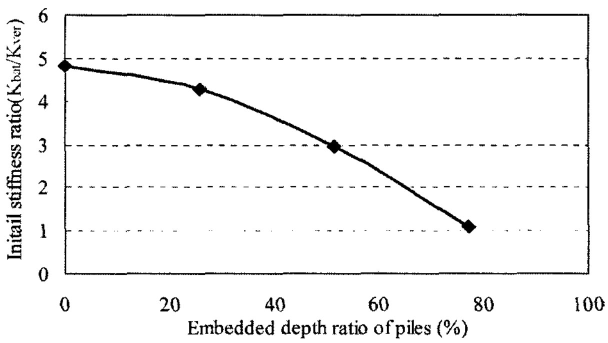
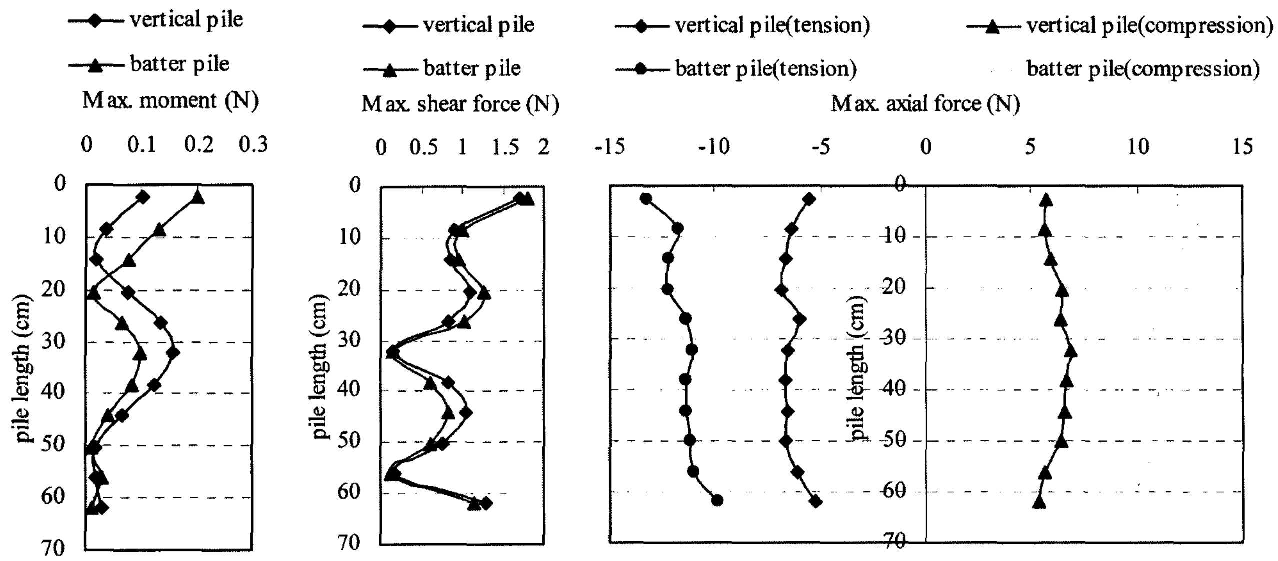


Fig. 5. Initial lateral stiffness ratio of batter and vertical pile according to embedded depth ratio of piles



(a) Max. moment (b) Max. shear force (c) Max. axial force

Fig. 6. Maximum member forces of vertical and batter pile

Table 1. Maximum member forces at pile head and max. acceleration and max. displacement at deck plate

Type of pile	Max. member forces at pile head			Max. acc. and max. disp. at deck plate	
	Max. moment (N-m)	Max. shear force (N)	Max. axial force (N)	Max. acc. (g)	Max. disp. (mm)
Vertical pile	0.100	1.700	5.740	0.162	0.110
Batter pile	0.200	1.810	13.230	0.167	0.020

force, and axial force developed on the batter and vertical pile when the input motion is a sinusoidal wave with a frequency of 10 Hz and an acceleration of 0.1 g. Under dynamic lateral loading, not only the moments but also the axial forces more heavily occur on the batter pile than the vertical pile. This tendency also appears when the soil depth is different. In Table 1, the maximum member forces at the pile head, and maximum acceleration and maximum displacement at the deck plate are compared between the batter and vertical piles. It shows that the batter pile plays a role in decreasing the acceleration and displacement at deck plate but tends to be more susceptible to be damaged by dynamic loading because of increase of moment and axial force at the pile head than the vertical pile.

3.2 Countermeasures for Improving Seismic Performance of Batter Pile

When dynamic loadings are exerted to batter piles, the batter piles are more susceptible to be damaged than vertical piles because the bending moment and axial force are largely generated at the pile head, as shown in Chapter 3.1. Countermeasures for improving this poor seismic performance of batter pile include introduction of a rubber element at the pile head and the deck plate connections, and introduction of hinge connection.

Modifications of pile head connections

The pile head connections are modified to improve the seismic performance of batter piles. Model tests are performed by changing pile head connection with *fix*, *hinge*, *rubber20* (hardness 20), and *rubber40* (hardness 40). Test conditions are that the soil depth is 36 cm, and the slope of batter piles is V:H (Vertical to Horizontal)=8:2. Seismic performance is measured through the maximum member forces at pile head, and maximum acceleration and displacement at deck plate. Figure 7 shows the result of static lateral load tests. In this figure, the initial lateral stiffness of *rubber20* and *rubber40* is smaller than that of *fix*. It is thought that the surrounding rubber of the pile head is too thick to maintain the lateral bearing capacity of *fix*. In the Table 2, the maximum accelerations at deck plate are compared according to the input motions. In the case of sinusoidal wave of 10 Hz in frequency, and 0.1 g in magnitude, the maximum acceleration took place in the case of *rubber20* and *rubber40*. From the results of impact load tests, the natural frequencies in the case of *hinge*, *rubber20*, and *rubber40* are 22, 9.3, and 10 Hz, respectively. Therefore, the larger acceleration is developed on the pile head connections of *rubber20* and *rubber40* because the frequency of input motion is equal or similar to the natural frequencies in the case of *rubber 20* and *rubber 40*. Because the response of the model pile system is largely influenced by the frequency of the input motion, the historical earthquakes having various frequency components are used in the model tests. In the case of historical earthquakes, when the maximum accelerations at the deck plate are compared for the different types of pile head connection, special tendency is not represented. However, when the pile head connections are *hinge* and *rubber20*, small acceleration has developed.

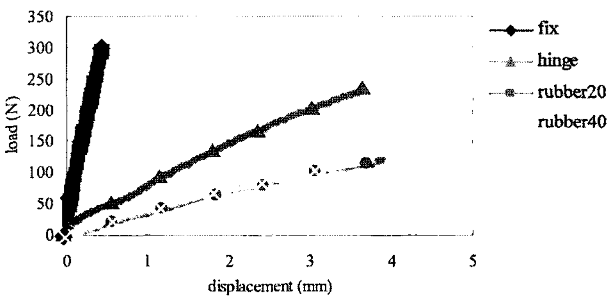
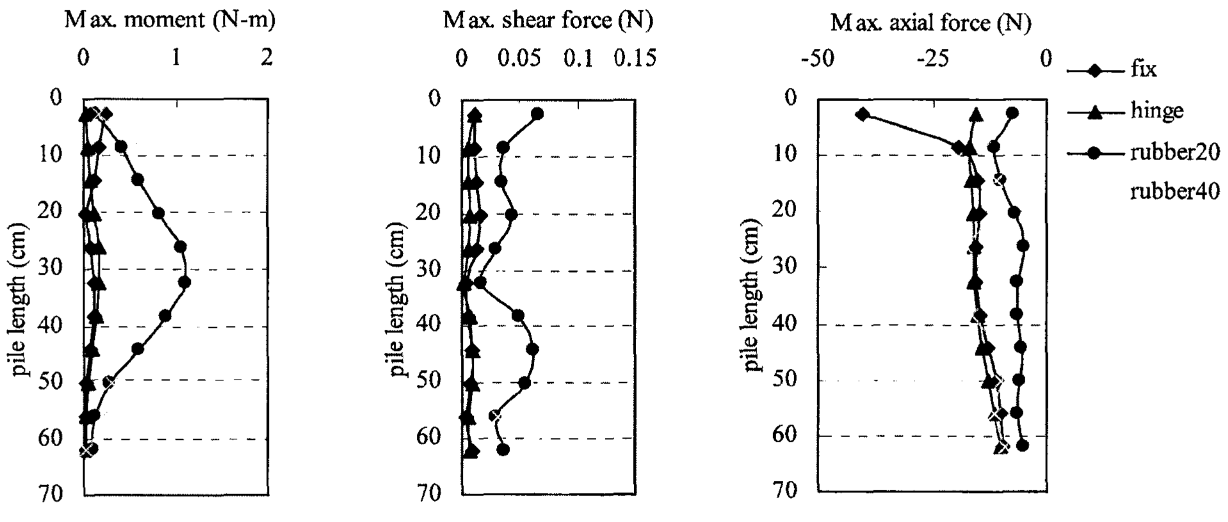


Fig. 7. Static load-displacement curves according to the pile head connections

Figure 8 shows the maximum member forces according to the pile head connections in the case of El Centro earthquake, and Table 3 shows the maximum member forces at the pile head, the maximum acceleration and displacement at the deck plate quantitatively. From Figure 8 and Table 3, the maximum moments and maximum axial

Table 2. Maximum acceleration at deck plate according to pile head connections

Connection conditions of pile head	Max. acceleration at deck plate (g)		
	Sine wave, 10 Hz, 0.1g	Hachinohe EQ., 0.11 g	El Centro EQ., 0.11 g
Fix	0.222	0.010	42.155
Hinge	0.043	0.015	24.833
Rubber20	0.125	0.066	4.833
Rubber40	0.086	0.064	7.210



(a) Max. moment (b) Max. shear force (c) Max. axial force

Fig. 8. Maximum member forces of vertical and batter piles for different types of pile head connection

Table 3. Maximum member forces at pile head and maximum acceleration and displacement at deck plate for different types of pile head connection

Connection conditions of pile head	Max. member forces at pile head			Max. acc. and max. disp. at deck plate	
	Max. moment (N-m)	Max. shear force (N)	Max. axial force (N)	Max. acc. (g)	Max. disp. (mm)
Fix	0.222	0.010	42.155	0.267	0.018
Hinge	0.043	0.015	24.833	0.211	0.259
Rubber20	0.125	0.066	4.833	0.298	0.890
Rubber40	0.086	0.064	7.210	0.259	0.923

forces decreased much in the pile head connection of *rubber20* and *rubber40* than the pile head connection of *fix*. Therefore, when the pile head connection is *rubber20* and *rubber40*, it is inferred that seismic performance of batter pile is improved.

Variation of slope of batter piles

Generally, batter piles are constructed with a range from 1 horizontal to 12 vertical to 5 horizontal to 12 vertical (Bowles, 1997). Shaking table tests are performed to find out the slope of batter pile which induces the minimum pile forces during the dynamic loadings varying a slope of the batter pile by V:H=8:1, 8:2, 8:3, and 8:4. The soil depth is 36 cm, and the pile head connection *fix*. Figure 9 shows the maximum member forces of the batter pile according to the slope of the batter piles when the input motion is sinusoidal wave, 10 Hz in frequency and 0.1g in magnitude. Table 4 is the quantitative comparison results of the maximum member forces at the pile head, and the maximum acceleration and maximum displacement at the deck plate according to the slope of batter pile. From Figure 9 and Table 4, when the slope of batter pile is V:H=8:1 and 8:2 the maximum member forces are larger than those of the vertical pile, but when V:H=8:3 and 8:4 these are smaller. Especially, when the slope of the batter pile is V:H=8:3 the maximum moment, maximum shear force and maximum axial force show the minimum value. As the slope of the batter pile increases, the maximum acceleration at the deck plate decreases. Maximum displacement at the deck plate is the smallest in the slope of the batter pile, V:H=8:2. Similar tendency is also shown in the input motion of 20 Hz, 0.1 g sinusoidal wave.

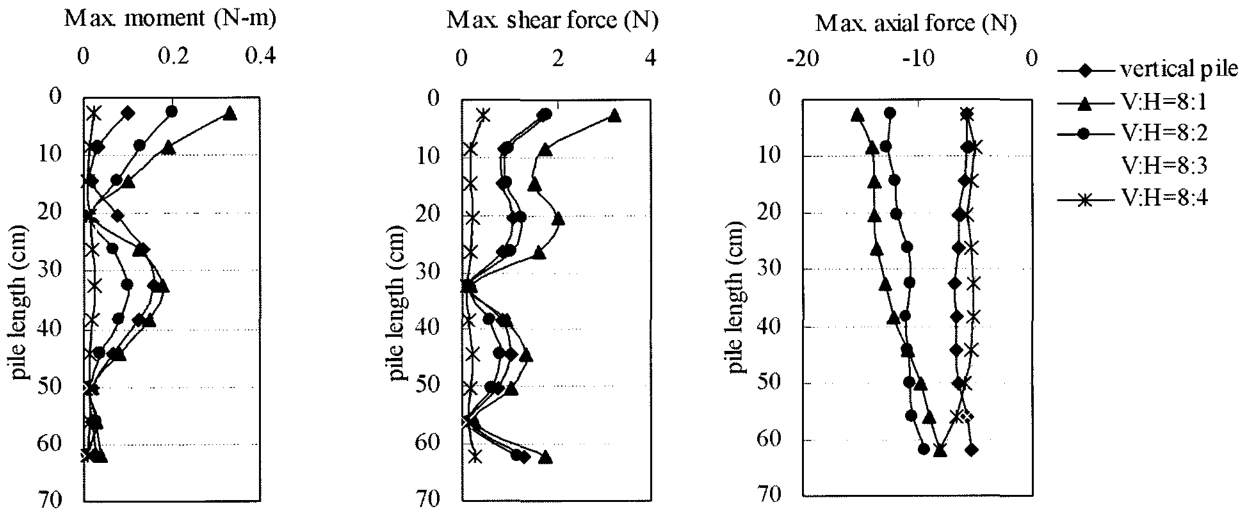


Fig. 9. Max. member forces of batter pile according to slope of batter pile

Table 4. Maximum member forces at pile head and maximum acceleration and displacement at deck plate according to slope of batter pile

Slope of pile		Max. member forces at pile head			Max. acc. and max. disp. at deck plate	
		Max. moment (N-m)	Max. shear force (N)	Max. axial force (N)	Max. acc. (g)	Max. disp. (mm)
Vertical pile		0.101	0.017	5.741	0.162	0.106
Batter pile	V:H=8:1	0.331	0.032	14.255	0.218	0.052
	V:H=8:2	0.203	0.018	13.225	0.167	0.022
	V:H=8:3	0.021	0.005	4.070	0.160	0.041
	V:H=8:4	0.026	0.004	5.669	0.149	0.046

4. Conclusions

Shaking table tests are performed to analyze the dynamic behaviors of vertical and batter piles and to develop the countermeasures for improving the seismic performance of batter piles. The following results are obtained.

(1) It is demonstrated that the group piles with batter piles resist to the static lateral load more effectively than those with only vertical piles.

(2) Vulnerability of batter piles under dynamic loadings is confirmed by the observation of the pile forces exerted in the pile heads during the shaking table tests.

(3) Countermeasures, using rubber elements at the pile head and the deck plate connection and hinges, to overcome the vulnerability, are tested and proved to be effective, even if the details of the rubber element design are not settled yet.

(4) The slope of batter piles which induces the minimum pile forces is found to be 8:3 (vertical to horizontal).

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