

# Article

# Dynamic Behavior of Pile-Supported Structures with Batter Piles according to the Ground Slope through Centrifuge Model Tests

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**Abstract:** Pile-supported structures incorporating batter piles are commonly used, and can be installed both on the horizontal and inclined ground. Recent studies have considered the positive role of batter piles during earthquakes, highlighting their satisfactory contribution to structural seismic performance. However, in these structures, even though the dynamic system responses can vary greatly depending on the ground slope, few previous studies have evaluated the seismic performance of batter piles relative to the ground slope. Therefore, this study evaluates the seismic performance of pile-supported structures with batter piles, relative to the ground slope using dynamic centrifuge model tests. The acceleration, displacement, moment, and axial force of the system were experimentally derived and reviewed, and the pile moment and axial force (*M*–*N*) interaction diagrams of the pile cross-sections were analyzed. The installation of the batter piles resulted in a greater reduction in the system response in the inclined-ground model (acceleration: -48%, displacement: -50%, and moment: -77%). Overall, batter piles showed better seismic performance in the inclined-ground model.

Keywords: pile-supported structure; dynamic centrifuge model test; batter pile

## 1. Introduction

Batter piles are widely used to resist lateral loads from such as earthquakes, wind, and waves. Batter piles are advantageous as they can transmit lateral load partly in the form of axial force, rather than shear and bending alone. In contrast, vertical piles carry the lateral load through shear and bending [1]. Additionally, when the batter pile is installed, it is possible to secure an effective bearing capacity by supporting it on the bedrock. However, certain historical cases have highlighted their potential negative effects in supporting structures during earthquakes [2]. In the US, the 1989 Loma Prieta earthquake damaged the wharf at the Port of Oakland, and the Northridge earthquake, in 1994, damaged the Los Angeles wharf. In both cases, tensile failure occurred at the head of the batter piles. In Japan, the 1995 Kobe earthquake buckled the batter piles in a wharf in the Sumiyoshihama region, causing horizontal displacement of about 1 m, tilting the structure was ~2–5° [3,4]. In the Philippines, the 1990 7.8 magnitude earthquake damaged the Port of San Fernando, opening many gaps in the longitudinal direction of the concrete deck, including one that was 0.7 m in size. Additionally, the cracks and chopping were observed on the vertical and batter pile caps, that exposed the reinforcing steel bars [4].



Several reports have identified the following problems of batter piles during earthquakes. A large force at the pile cap can undesirably, and permanently, rotate it due to the asymmetry of the pile. Additionally, the bending moment capacity can be reduced by the seismically induced tensile forces [1]. Thus, certain codes do not recommend the application of batter piles in seismic design. For instance, the French Seismic Code [5] suggests that batter piles should not be used to resist seismic loads, and the Eurocode [6] recommends not to use them to transmit lateral loads to the soil. The Korean Ministry of Ocean and Fisheries [7] also recommends that batter piles should not be installed as they are easily damaged at their connection with the top plate.

However, some researchers have reported the positive role of batter piles. Numerical analysis by Gerolymos et al. [8] demonstrated satisfactory seismic performance of both the superstructure and the foundation when batter piles are properly designed. Harn [9] argued that the past seismic damage of batter piles was caused by the lack of engineering knowledge and numerical modeling techniques and that it is possible to secure positive performance by applying advanced numerical analysis and appropriate design methods.

Recently, several studies have been conducted using dynamic experimentation to evaluate the performance of batter piles considering multiple variables, such as bottom condition, input motion, and structure size. Escoffier et al. [10] conducted dynamic centrifuge model tests on pile groups consisting of one by two vertical piles, and one by two pile group with one batter pile. The bottom was classified as end-bearing, or a floating pile group, to evaluate the performance of batter piles with respect to the conditions at the bottom of the pile. Horizontal cyclic loading and horizontal impact tests were performed on each pile. The installation of the batter piles reduced the moments of both piles. Escoffier [11] also performed a dynamic centrifuge model test by applying repeated earthquake and sinusoidal inputs to the model, previously used by Escoffier et al. [10]. The soil response, pile cap response, and stresses in the piles were comprehensively reviewed. The test results showed that the batter piles were significantly affected by the frequency characteristics of the input wave. Li et al. [12] conducted dynamic centrifuge model tests to evaluate the behavior of vertical and batter piles. They analyzed the characteristics of the batter piles corresponding to their natural frequency and size of structures. They confirmed that the performance of the batter piles degraded when the applied sinusoidal wave was in the region of the structure's natural period, and improved when the structure's natural period was in the region of that of the soil. Similarly, Li et al. [13] analyzed the behavior of batter piles relative to the size of the structures by applying earthquake excitation. The batter piles had positive effects on the structure in terms of displacement and force and, overall, showed positive performance, especially in short structures. Bharathi et al. [14] conducted field tests on structures with vertical and batter piles, analyzing the effects of the batter piles on the frequency and the number of piles. A mechanical oscillator was installed on the pile cap to apply a sinusoidal load. The batter piles significantly reduced the displacement with increasing load. Overall, various studies have considered the seismic performance of batter piles corresponding to a range of variables and have found that excellent seismic performance can be observed when an appropriate design method is applied.

Recently, several studies have been conducted in this dynamic domain using numerical analysis. Giannakou et al. [1] assessed variables using a three-dimensional numerical analysis to evaluate the effects of batter piles. They found that the overturning moment varied depending on the size of the structure, and the impact of the batter piles depended on parameters such as structure size, pile rake, and pile-cap connection. Chen and Hsu [15] performed three-dimensional analysis using FLAC 3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) to understand the behavior of batter pile foundations subjected to lateral soil movement. Numerical analysis was performed on a three by three group pile combined with vertical piles of batter piles. The response of the group pile to soil movement was analyzed and revealed that the maximum moment of the batter piles was smaller than that of the vertical piles in sand, but was five to eight times higher than in clay. Similarly, Sarkar et al. [16] performed three-dimensional analysis to evaluate the seismic behavior of a two by two vertical and batter pile, with a batter angle of 15°, was

compared using a full three-dimensional finite element code, developed in MATLAB. The comparison of the response of the frame structures of the five stories showed that the response in the structure with a batter pile foundation was reduced by  $\sim$ 12%–50%, compared to the structure with a vertical pile foundation.

Batter piles are widely used in wharves, piers, and jetties. Wharves are generally built on inclined ground, and piers and jetties, on horizontal ground [17] (Figure 1). A structure's performance during an earthquake can vary greatly depending on the slope of the ground. Yun and Han [18] conducted a dynamic centrifuge model test to examine structural responses corresponding to the ground slope and explained that the kinematic force of the slope causes an additional response in the pile. However, they evaluated the seismic performance of only vertical piles. This highlights that current research on the seismic performance of batter piles with respect to the ground slope is insufficient.



(a)

(b)

Figure 1. Pile supported structures: (a) a Henley beach jetty, South Australia and (b) a wharf [17].

In this study, dynamic centrifuge model tests were performed to evaluate the seismic performance of batter piles with respect to the ground slope. Four test models were selected according to the presence or absence of batter piles and the ground slope. When designing the batter pile of a pile-supported structure, an inclination between 3:1 and 5:1 was used with respect to the positional constraints of the other piles and the constructional constraints, such as the driving machine [19]. The inclination of 3:1 (18°) was used so that the batter pile could properly support the lateral force. The acceleration, displacement, and axial force of the system are reviewed, and the interaction diagram of the pile cross-sectional bending moment (M) and axial force (N), gathered from the test, were plotted to evaluate the seismic performance of the batter piles.

#### 2. Dynamic Centrifuge Model Testing

Centrifuge model tests were conducted to evaluate the seismic performance of pile-supported structures with batter piles. The models were spun in the centrifuge to increase the g-level in them so that stresses in their ground were equal to those in the prototype. It is also an advantage for the theoretical verification and numerical analysis techniques as the boundary and stress conditions of the ground, which are imposed in the centrifuge model test, have been studied a lot [10–13]. The tests were carried out at the Korea Advanced Institute of Science and Technology (KAIST) Geo-centrifuge Testing Center using an experimental machine with a 5 m radius and 240 g-ton maximum operating capacity [20–22]. The experiments used a square-equivalent shear beam model box (49 cm by 49 cm by 69 cm) that behaved similarly to the ground, reducing the effect of the wall reflections [23].

Certain sections of the pile-supported structures at the Port of Pohang, Korea, were modeled for the tests. This study used experimental models previously tested by Yun et al. [24]. Figure 2 shows the testing procedure of the HAI55 model in detail. First, the base plate and the piles were installed to the equivalent shear beam (ESB) box, and the relative density of the ground was adjusted through the air pluviation method. The inclined ground was composited, and the test was performed after installing

the deck plate and the instrumentations. The soil was simplified to a single-component sandy soil. Figure 3 shows the four model configurations tested. Models HA45 and HAI55 had horizontal grounds with relative densities of the soil being 45% and 55%, respectively. Models IA62 and IAI58 had inclined grounds with relative densities of the soil being 62% and 58%, respectively. Models HA45 and IA62 had nine piles in the  $3 \times 3$  arrangement shown in Figure 4a,c. Models HAI55 and IAI58 had a similar  $3 \times 3$  pile arrangement with four additional batter piles, as shown in Figure 4b,d. Each model was 1/48 in scale, and the specifications were calculated by adjusting the flexural rigidity, which has the highest impact on structural behavior during an earthquake. Table 1 presents the scaling laws linking the prototype and the model, and Table 2 lists their properties. The model piles and deck plates were made of aluminum (elastic modulus, E = 68,300 MPa; Poisson's ratio, v = 0.3) [25–27].



(e) Performing the centrifuge model test







Figure 3. Model cross-section: (a) HA45 model; (b) HAI55 model; (c) IA62 model; and (d) IAI58 model.





(b)



(c)



**Figure 4.** Plan view of experimental model before installing the deck plate: (**a**) HA45 model; (**b**) HA155 model; (**c**) IA62 model; and (**d**) IA158 model.

	Centrifuge Scale Factors	Centrifuge Scale Values		
Acceleration (g)	$n^{-1}$	0.021		
Velocity (m·s <sup>−1</sup> )	1	1		
Length (m)	п	48		
Time (dynamic) (s)	п	48		
Mass density ( $kN \cdot m^{-3}$ )	1	1		
Mass (kg)	$n^3$	110,592		
Force (kN)	$n^2$	2304		
Stress ( $kN \cdot m^{-2}$ )	1	1		
Pile stiffness (EI) ( $kN \cdot m^2$ )	$n^4$	5,308,416		
Moment (kN·m)	$n^3$	110,592		

Table 1. Model scaling factors and values.

Table 2. Prototype and model properties (scale factor = 48).

		Prototype (Steel Pile)	Model (Aluminum Pile)
	Diameter (mm)	914	19
	Thickness (mm)	14	1
Pile	I on oth (mm)	24,000	500
	Lengui (mm)	(batter pile: 24,900)	(batter pile: 519)
	Density (kN⋅m <sup>-3</sup> )	78.5	26.4
	Flexural rigidity (kN·m <sup>2</sup> )	$7.81 \times 105$	0.147
	Inclination angle of batter pile	3:1	3:1
Deck	Thickness (mm)	1000	20
	Density ( $kN \cdot m^{-3}$ )	24.5	26.4

Artificial seismic waves (Figure 5a), suitable for Korean sites, were produced, as specified by the Ministry of Oceans and Fisheries (MOF) [19]. The design ground acceleration, considering the ground characteristics, is expressed as a response spectrum curve, and a 5% damping ratio is generally applied. Figure 5b compares the response spectrum curve of the artificial seismic wave and the standard design response spectrum curve, showing their close agreement. Figure 5b also shows the natural periods of the soil-pile system of each model of the centrifuge model test. It shows the natural periods of 0.5–0.65 s. As the confining pressure of the ground near pile 3 (landward pile) was larger in the inclined ground model (IA62) than in the horizontal ground model, the ground stiffness was relatively higher than that in the horizontal ground model (HA45). This resulted in a smaller natural period in the inclined ground model (IA62) than the horizontal ground model (HA45), as shown in Figure 5b. Table 3 lists the base input seismic motion applied to each model.



**Figure 5.** Input ground acceleration: (**a**) input seismic wave and (**b**) comparison of the response spectra and natural periods of soil-pile system

	Horizontal G	round Model	Inclined Ground Model		
Model	HA45	HAI55	IA62	IAI58	
Relative density (%)	45	55	62	58	
-	0.09	0.07	0.05	0.08	
	0.14	0.12	0.12	0.12	
Input peak acceleration (g)	0.15	0.15	0.18	0.14	
	0.18	0.2	0.21	0.19	
	0.23	0.26	-	0.24	

Table 3. Seismic motion input for each model.

The tests were conducted in dry sand to minimize the effects of liquefaction and lateral spreading on the piles, which can occur when considering pore water pressure. The tests used silica sand with an average particle diameter ( $D_{50}$ ) of 0.3 mm, the basic properties of which are listed in Table 4. The sand used in this test was classified as poorly graded sand (SP) according to the Unified Soil Classification System. It had a coefficient of uniformity ( $C_u$ ) of 1.96, and its coefficient of curvature ( $C_c$ ) was 1.16. Its specific gravity ( $G_s$ ) was 2.63, maximum dry unit weight was 16.5 kN·m<sup>-3</sup>, and its minimum dry unit weight was 12.4 kN·m<sup>-3</sup>. As explained earlier, the relative density of the ground was adjusted by air pluviation. However, minor differences were observed in the relative density of each model due to a defect in the air pluviation machine. The piles were fixed to the base plate to simulate the end-bearing pile. Laser displacement meters, potentiometers, linear variable differential transformers (LVDTs), accelerometers, and strain gauges were used, as seen in Figures 2 and 3. Figure 3a,c show the positions of the laser displacement meters used to derive the displacement. These displacement meters easily measure the residual displacement but cannot accurately measure the displacement value over time. Therefore, as seen in Figure 3b,d, displacements were derived using LVDTs and potentiometers that measure displacement over time.

Soil Type	Silica Sand
USCS	SP
$C_c$	1.16
$C_u$	1.96
$G_s$	2.63
$\gamma_{d.max}$ (kN·m <sup>-3</sup> )	16.5
$\gamma_{d.min}$ (kN·m <sup>-3</sup> )	12.4

Table 4. Properties of silica sand.

#### 3. Centrifuge Test Results and Discussion

Many researchers have considered pile bending moment, axial force, and horizontal displacement to evaluate the seismic performance of such structures [12,13,28]. Seismic design codes for pile-supported structures consider the lateral load. PIANC [4] evaluated the residual tilting of piles to account for the horizontal displacement of a structure during an earthquake, and the MOF [19] evaluated member performance using the maximum moments and axial force during an earthquake. Therefore, this study derived the acceleration of the ground and the structure, residual displacement of the structure, pile moment, and the axial force from the dynamic centrifuge model test. The relationship between the moment and the axial force was analyzed to assess the performance of the member.

Figures 6 and 7 compare the acceleration time history and response spectrum curves of each model; all the test data show the prototype response. Figure 6 shows the responses of the horizontal-ground models (HA45 and HAI55) for a peak input acceleration of 0.15 g. Results for the bedrock and ground surface acceleration (A1, A2) show a similar trend for the two models, despite a 10% difference in their ground relative densities. In contrast, their deck plate accelerations (A3) were varied significantly.

Particularly, when the batter piles were installed, the response decreased in the long-period region  $(\geq 0.45 \text{ s})$  as the stiffness of the system increased.



Figure 6. Acceleration time histories of horizontal ground model (0.15 g) (scaled to the prototype).



Figure 7. Acceleration time histories of inclined ground model (0.12 g) (scaled to the prototype).

Figure 7 shows the responses of the inclined-ground models, IA62 and IAI58, to a peak input acceleration of 0.12 g. The results for the bedrock and ground surface acceleration (A1, A2) show no

significant difference in model responses. In contrast, their deck plate accelerations (A3) were varied greatly. Even in the case of the inclined ground model, when batter piles were installed, the response decreased in the long-period region ( $\geq 0.35$  s) as the stiffness of the system increased.

Figures 8 and 9 show the time history curves of the moments and axial forces along the piles for each model. The strain gauges were placed in pairs on the exterior of the piles to derive the pile moments and axial forces (Figure 4a). When a pile bends, tensile force is generated on one side, and compression force on the other, such that strains having opposite signs are derived from both strain gauges. When the axial force occurs in the pile, strains having the same signs are derived. Therefore, the sum of the strains on each side was divided by two to calculate the axial force, and the difference between each side strains was divided by two to calculate the moment. Equations (1) and (2) show the calculation process of the pile axial force (*N*) and the pile bending moment (*M*), respectively.

$$N = EA \cdot \frac{\varepsilon_1 + \varepsilon_2}{2} \tag{1}$$

$$M = \frac{EI}{y} \cdot \frac{\varepsilon_1 - \varepsilon_2}{2} \tag{2}$$

here, *EA* is the pile axial stiffness (kN), *EI* is the pile bending stiffness (kN m<sup>2</sup>),  $\varepsilon_1$ ,  $\varepsilon_2$  is the pile strain value at both sides, and *y* is the pile diameter (m).



**Figure 8.** Pile moment and axial force time histories of horizontal ground model (0.15 g) (scaled to the prototype).



**Figure 9.** Pile moment and axial force time histories of inclined ground model (0.12 g) (scaled to the prototype).

Figure 8 shows the responses of models HA45 and HAI55 (0.15 g), and Figure 9 shows those of models IA62 and IAI58 (0.12 g). As shown in Figure 7, the installation of batter piles to the horizontal-ground model significantly reduced the moments of the vertical piles (S1–S3), whose maximum moment was reduced by 88%, 73%, and 79%, respectively. The axial forces (S4, S5) of the batter piles were large, up to a maximum of 1744 kN. Figure 9 shows similar results wherein the batter piles reduced the maximum moments of the vertical piles (S1–S3) by 70%, 74%, and 79%, respectively, and the axial forces (S4, S5) of the batter piles were very large, up to a maximum of 1499 kN.

Figure 10 (models HA45 and HAI55; 0.15 g) and 11 (IA62 and IAI58; 0.12 g) show the vertical pile moment and the batter pile axial force along the depth of each model. The vertical pile moment responses were derived according to the direction of the pile movement (toward the sea or land). The batter-pile axial force responses were derived according to tension and compression. The figures show the responses by the depth at the time of the maximum response. The moment in the lower part of pile three, in model HAI55 (Figure 10), was not measured due to an instrumentation error.

The vertical pile moments, presented with respect to the depth for piles one to three in Figure 10, show that the maximum moment occurred mostly at the top of the pile, and the greatest moment with the opposite sign occurred at a depth of 10 m. The moment converged to zero at a depth of 16 m. The plots of the moment by depth were similar for all piles. Batter piles significantly reduced the vertical pile moment, and both batter piles showed consistent axial force at all depths.

The plots of the vertical pile moment by depth, for piles one to three in Figure 11, show the maximum moment at the top of each pile. A comparison of the inclined-ground models shows that the batter piles significantly reduced the vertical pile moment. The axial force of the batter piles also depended on the pile. Batter pile four showed constant axial force at all depths. In contrast, batter pile five had a lower axial force at its base. Its deep penetration in the soil potentially reduced the transmission of the upper load as the skin friction force increased.



**Figure 10.** Depth profiles of maximum moment and axial force of horizontal ground model (0.15 g) (scaled to the prototype).



**Figure 11.** Depth profiles of maximum moment and axial force of inclined ground model (0.12 g) (scaled to the prototype).

The batter piles reduced the maximum moment of the vertical piles by 88% and encountered large axial forces. The vertical pile moment reduced as the lateral load of the earthquake was transmitted to the axial force in the batter pile. This finding is similar to that of the dynamic centrifuge model test for pile groups by Escoffier et al. [10] and Li et al. [12]. Escoffier et al. [10] found that using batter piles reduced the maximum moment of the vertical piles and increased the axial force by 1.7 times in the front (batter) pile, and doubled it in the rear (vertical) pile. Li et al. [12] reported that the pile moment and axial force depended on the size of the structure and the applied frequency. Under a 3.5 Hz sine wave, the maximum moment was reduced in the batter pile group regardless of the structure size. The axial force decreased for a small structure with a batter pile group (about 7 m depth) and increased for a large structure (about 16 m depth). The results obtained from this study for a pile-supported structure with sufficiently long piles were similar to those obtained by Li et al. [12].

Figures 12 and 13 plot the peak acceleration of the deck plate (A3), the horizontal residual displacement of the deck plate (L1, PM6), the maximum moment of the vertical piles (S3), and the maximum axial force of the batter piles (S4), corresponding to the input acceleration for each model. The vertical pile moments were derived at the pile top (S3), where the maximum moment was observed. The plotted axial forces of the batter piles were also derived at the pile top (S4). As four to five datasets were derived per test in this study, regression analysis curves were also plotted to obtain the intermediate value. Quadratic polynomials were derived using the least square method.



**Figure 12.** Response of horizontal ground model corresponding to the input acceleration. (scaled to the prototype): (**a**) peak acceleration of deck plate; (**b**) horizontal residual displacement of deck plate; (**c**) maximum moment of vertical pile; and (**d**) maximum axial force of batter pile.



**Figure 13.** Response of inclined ground model corresponding to the input acceleration. (scaled to the prototype): (**a**) peak acceleration of deck plate; (**b**) horizontal residual displacement of deck plate; (**c**) maximum moment of vertical pile; and (**d**) maximum axial force of batter pile.

The peak acceleration and residual displacement of the deck plate in both figures show that the response increased with the input acceleration, for both horizontal and inclined ground models. The batter piles had little effect at low input motion intensities (less than 0.1 g), although their influence increased with the input motion intensity. The batter piles decreased the residual displacement in the inclined-ground model, but more than doubled it in the horizontal-ground model. The maximum moments of the vertical piles in Figures 12 and 13 changed significantly when the batter piles were installed. Both the horizontal- and the inclined-ground models had significant axial force in the batter piles, as the vertical pile moment is reduced when a batter pile is installed because the lateral earthquake load is transmitted to the axial force.

The differences in the system responses were derived to evaluate the performance of the batter piles according to the ground slope. The bar graphs in Figure 14 express the change in system response according to the installation of the batter piles. A negative value indicates that the batter piles decreased the response, while a positive value indicates an increased response.













**Figure 14.** Difference in response with and without the batter pile according to the ground slope: (a) peak acceleration of deck plate; (b) horizontal residual displacement of deck plate; and (c) maximum moment of vertical pile.

The peak acceleration of the deck plate (Figure 14a) decreased when the batter piles were installed in all cases, except for the horizontal-ground model with 0.09 g input acceleration. The batter piles reduced the peak acceleration of the deck plate significantly as the input acceleration increased; the decrease was more significant in the inclined-ground model (up to 48%) than in the horizontal-ground model (up to 27%). The residual displacement of the deck plate (Figure 14b) increased significantly when the batter piles were installed in the horizontal-ground model but decreased in most cases for the inclined-ground model. The increase observed in the horizontal-ground model resulted from the asymmetry of the structure in the landward and seaward directions, as the batter piles were installed close to the seaward side, as shown in Figure 3. However, in the inclined-ground model, the residual displacement of the deck plate decreased because the batter piles constrained the structure's behavior. Figure 14c shows that the batter piles reduced the maximum moment of the vertical pile more significantly in the inclined-ground model (by up to 84%) than in the horizontal- ground model (up to 77%). A large difference was observed in the peak acceleration and residual displacement in the response based on the installation of batter piles. However, in the case of the pile's maximum moment, the difference in response to the installation of batter piles was not large. This is because the batter pile carries most of the lateral load, so the moment of the vertical piles is significantly reduced in both the horizontal and inclined ground models.

Table 5 shows the system responses. For the models without batter piles, the system response was greater in the inclined-ground model (IA62) than in the horizontal-ground model (HA45). This is because an additional kinematic force may be generated in the inclined ground during an earthquake, and the system response increases significantly [18,29]. However, when the batter piles were installed, the system response significantly reduced in the inclined-ground model (IAI58), compared to that in the horizontal-ground model (HAI55) because the lateral resistance greatly increased when the batter piles were installed to the former model. However, installing the batter piles to the horizontal-ground model increased the lateral resistance and the asymmetry of the system. Hence, the response reduction was not significant. Thus, the batter piles performed better in the inclined-ground model than in the horizontal-ground model.

	Horizontal Ground Model					Inclined Ground Model				
	Input acc. (g)	0.09	0.13	0.17	0.21	Input acc. (g)	0.09	0.13	0.17	0.21
Peak acc. of deck	HA45	0.21	0.31	0.39	0.44	IA62	0.25	0.36	0.49	0.62
plate (g)	HAI55	0.22	0.26	0.29	0.32	IAI58	0.20	0.26	0.30	0.32
F (9)	Diff. (%)	4	-17	-25	-27	Diff. (%)	-19	-30	-40	-48
Horizontal residual	HA45	1.20	1.06	2.30	4.94	IA62	5.12	19.69	40.99	69.02
displacement of	HAI55	3.75	7.91	12.34	17.03	IAI58	6.59	15.81	25.13	34.57
deck (mm)	Diff. (%)	212	650	436	245	Diff. (%)	29	-20	-39	-50
Maximum moment of vertical pile (kN·m)	HA45	571	892	1134	1297	IA62	754	1103	1473	1863
	HAI55	160	209	256	303	IAI58	190	230	268	304
	Diff. (%)	-72	-77	-77	-77	Diff. (%)	-75	-79	-82	-84

Table 5. Difference in system response with and without the batter pile.

The member stress of the pile is calculated by combining pile moment (M) and axial force (N). Installing batter piles can degrade the bending capacity of a member due to the increase in the axial force [1]. Therefore, it is important to consider both the bending moment and the axial force of the pile to evaluate the member performance. M–N curves are widely used to evaluate the cross-sectional member force when M and N occur simultaneously in monolithic beam [30]. They are also called the M–N interaction diagrams because the two cross-sectional forces influence each other and are a crucial method for evaluating the seismic performance of bridges.

The MOF [7] proposes a method for evaluating the performance of the pile-supported structure with batter piles under static load. However, a method to properly evaluate the seismic performance of a structure with a batter pile has yet to be formulated as its use has been avoided in seismic design. Therefore, this study used the performance evaluation method, under static load, proposed by the MOF [7] in seismic design. Accordingly, an M-N interaction diagram was derived during an earthquake to evaluate the member force of the structure with batter piles. The code first explains that axial force and bending moment are converted into sectional stresses. Equations (3) and (4) show the axial stress ( $f_n$ ) and the bending stress ( $f_m$ ), respectively.

$$f_n = \frac{N}{A} \tag{3}$$

$$f_m = \frac{M}{Z} \tag{4}$$

here,  $f_n$  is the axial stress of pile (kN m<sup>-2</sup>),  $f_m$  is the bending stress of pile (kN m<sup>-2</sup>), A is the cross-sectional area of pile (m<sup>2</sup>), and Z is the section modulus of pile (m<sup>3</sup>).

For a member with *M* and *N* occurring simultaneously, the sectional stress should not exceed the allowable stress. Equations (5) and (6) explain the relationship between sectional stress and allowable stress divided into cases where the tensile and compressive forces occur, respectively.

$$f_t + f_{bt} \le f_{ta} \text{ or } - f_t + f_{bc} \le f_{ca} \tag{5}$$

$$\frac{f_c}{f_{ca}} + \frac{f_{bc}}{f_{ba}} \le 1.0\tag{6}$$

here,  $f_c$  is the compressive stress of pile (kN m<sup>-2</sup>),  $f_t$  is the tensile stress of pile (kN m<sup>-2</sup>),  $f_{bc}$  is the bending compressive stress (kN m<sup>-2</sup>),  $f_{bt}$  is the bending tensile stress (kN m<sup>-2</sup>),  $f_{ta}$  is the allowable tensile stress (kN m<sup>-2</sup>),  $f_{ca}$  is the allowable compressive stress (kN m<sup>-2</sup>),  $f_{ba}$  is the allowable flexural stress (kN m<sup>-2</sup>), and  $f_a$  is the allowable stress (kN m<sup>-2</sup>).

This study applied the allowable stress ( $f_{ta} = f_{ca} = f_{ba} = 185,000 \text{ kN m}^{-2}$ ) of STK490 steel to the actual prototype structure. As the allowable tensile, compressive, and flexural stresses are the same for STK49 steel, these can be expressed by Equation (7). For the member with *M* and *N* occurring simultaneously, the combined stress ratio (*F*) should not exceed one.

$$F = \left|\frac{f_n}{f_a}\right| + \left|\frac{f_m}{f_a}\right| \le 1.0\tag{7}$$

Figures 15 and 16 show the *M*–*N* interaction diagrams calculated using the above equations. The *x*-axis values were calculated by dividing the bending stress by the allowable stress, and the *y*-axis by dividing the axial stress by the allowable stress. Each graph represents the change in bending and axial stresses over time. When the plot is within the area delineated by the dotted lines, the *F* value does not exceed one. The bending and axial stresses of each figure are the responses at positions S3 and S4.

Figure 16 shows the time history responses when a low input acceleration (0.12–0.15 g) was applied. The plots for the horizontal (Figure 16a) and inclined (Figure 16b) ground models are slightly below the *x*-axis as the load on the deck plate acts as the axial stress. In the HA45 model, that is composed of vertical piles, as seen in Figure 16a, the bending stress ratio ( $f_m/f_a$ ) is relatively large compared with the axial stress ratio ( $f_n/f_a$ ). This model's derived maximum bending stress ratio and axial stress ratio were 0.67 and 0.15, respectively. The bending stress ratio for the vertical piles (0.14) was greatly reduced for Model HAI55, with the batter piles, the axial force ratio of which was 0.27. The inclined-ground models showed similar trends in Figure 16b because batter piles transmit a lateral earthquake load as an axial force, thereby reducing the moment generated in the pile.

The time history responses are shown in Figure 16a for the horizontal-ground model and in Figure 16b for the inclined-ground model when a high input acceleration (exceeding 0.2 g) was applied. Models HA45 and IA62 have relatively large bending stress ratios compared with the axial stress ratios in the vertical piles. Particularly in the IA62 model, a combined stress ratio exceeding one was derived despite the application of a lower input acceleration (0.21 g), compared to that applied to the HA45 model (0.23 g). This was because, for the inclined-ground models, as described above, the kinematic forces of the inclined ground generated additional kinematic forces in the piles. However, batter piles greatly reduced the bending stress ratio of the vertical piles, and the combined stress ratio decreased to less than one.



**Figure 15.** Relationship between bending moment and axial force (input peak acceleration ~0.12–0.15 g, scaled to the prototype): (**a**) horizontal ground model and (**b**) inclined ground model.



**Figure 16.** Relationship between bending moment and axial force (input peak acceleration exceeds 0.2 g, scaled to the prototype): (**a**) horizontal ground model and (**b**) inclined ground model.

Table 6 compares the combined stress ratio for each model derived using Equation (7). When the batter piles were installed, the combined stress ratio decreased in the vertical pile in both the horizontal and inclined ground models. The combined stress ratios of up to 0.62 in the horizontal ground and one in the inclined ground models decreased. Thus, the batter piles show more efficient performance on inclined ground than on horizontal ground. Even when the combined stress ratio exceeded one in the IA62 model, installing batter piles reduced it to a level below one to secure member stability. The results observed are similar to those of Jiren et al. [31], which show the relationship between moment and axial force as the *M*–*N* interaction curve. In the study, the size of the curve also reduced in the model with the batter pile. However, it was difficult to compare the effects of the ground slope in the study by Jiren et al. [31] because the effect of ground slope was not considered.

Table 6. Calculation of the combined stress ratio for each model.
-------------------------------------------------------------------

		Horizont	al Ground	Model	Inclined Ground Model			
Model		HA45	HAI55		IA62	IA	IAI58	
		VP *	VP	BP *	VP	VP	BP	
Combined stress ratio	Input acc. ~0.12–0.15 g	0.77	0.23	0.39	0.75	0.21	0.28	
	Input acc. exceeds 0.2 g	0.89	0.27	0.42	1.28	0.28	0.36	

\* VP (vertical pile), BP (batter pile).

The pile-supported structure is a port structure used for marine freight transportation, where a crane structure can be installed on the deck plate. As the crane structure is directly connected to the deck of the pile-supported structure, it is important to consider the seismic performance of the crane and the structure together to achieve the desired seismic performance [4]. Therefore, a study considering the dynamic interaction of soil-structure-crane is necessary.

In this study, the centrifuge model tests considering of the soil-pile interaction were conducted to evaluate the seismic performance of batter piles composed of steel pipe piles. However, for most structures, the reinforced concrete (RC) structures are more widely used than steel structure, and numerous damage to RC structures during earthquakes have been reported [32]. For example, the Mw 7.8 Nepal earthquake in 2015 resulted in the destruction of RC structure and local settlements [33,34]. In addition, Mw 6.0 Central Italy earthquake in 2016 caused significant damage to some RC structures and infra facilities [35]. RC structure are also widely used in the pile-supported structure, so studies of pile-supported structure considering the batter pile composed of RC piles will be necessary.

## 4. Conclusions

This study evaluated the seismic performance of pile-supported structures with batter piles with respect to the ground slope using dynamic centrifuge model tests. The acceleration, displacement, moment, and axial force of the system were experimentally derived and reviewed, and *M*–*N* interaction diagrams of the pile cross-sections were analyzed. The following conclusions were drawn.

- 1. Batter piles reduced the maximum moment of the vertical piles by 88%. A large axial force occurred in the batter piles, which conversely reduced the moment of the vertical piles as the lateral load was transmitted to the axial force in the batter piles.
- 2. The reduction in system response in the inclined-ground model (acceleration: -48%, displacement: -50%, and moment: -84%) was greater than that in the horizontal-ground model (acceleration: -27%, displacement: +650%, and moment: -77%) because the lateral resistance increased greatly when the batter piles were installed in the inclined ground model. Contrastingly, while batter piles in the horizontal-ground model increased the lateral resistance, they also increased the asymmetry of the system, the response is not significantly reduced.
- 3. *M*–*N* interaction diagrams were derived to evaluate the cross-sectional stress where both the bending moment and axial force occurred simultaneously. When the batter piles were installed, the combined stress ratios, of up to 0.62 in the horizontal ground, and up to 1 in the inclined ground, were reduced, showing efficient performance in the inclined ground. Even when the sectional stress originally exceeded the allowable stress, the batter piles could reduce it to within the allowable limit to secure member stability.
- 4. This comparison of the seismic performance of the batter piles, installed in the horizontal and inclined grounds, found that they can improve the results for acceleration, residual displacement, moment, and member stability for a structure on inclined ground, benefiting these structures than those on horizontal ground.

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