A Study on Dynamic Behaviors of Pile-supported Structures on Horizontal and Inclined Ground during an Earthquake

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ABSTRACT

Earthquake damage of pile-supported structures is generally influenced by the inertial force of the deck and the kinematic force between the soil and the piles. A pile-supported wharf built on a slope experiences a greater kinematic force compared to a pile-supported pier constructed on horizontal ground, due to slope failure as the ground shakes. In this study, a dynamic centrifuge model tests were conducted to analyze the dynamic behaviors of pile-supported structures installed on horizontal ground and inclined ground, during an earthquake. The experiments involved a 3 × 3 section of a pile-supported structure on horizontal and inclined grounds in Pohang, South Korea. The results showed the great impact on the moment of piles caused by the kinematic force between the soil and the structure, due to slope failure.

Keywords: Pile-supported wharf; Dynamic centrifuge model test; Seismic design; Ground slope; Port structure

1 INTRODUCTION

Pile-supported structure, essentially comprising a deck supported by piles driven into the ground, facilitates the loading and unloading of marine freight. Generally, a basic pile-supported structure consists of piles and deck. These structures can be classified into pile-supported wharves and piers, according to the structure type. Pile-supported wharves run parallel to the coast and exhibit a narrow width perpendicular to the shore. They are often built on inclined embankments sloping down toward the sea. On the other hand, pile-supported piers extend perpendicular to the coast and contain a base long enough to remain on the flat seabed (Balomenos and Padgett, 2017).

Pile-supported structures face the risk of severe damage during earthquake. A 7.8 magnitude earthquake occurring in the Philippines in 1990 significantly damaged the pile-supported piers at the San Fernando port. A horizontal displacement of 1.5 m occurred at the end of the piers in the longitudinal direction toward the sea owing to slope failure. Extensive cracks opened on the supported deck, with cracks and chips forming on the pile caps (PINAC, 2001). The 7.2 magnitude Hyogoken–Nambu earthquake of 1995 in Japan caused extensive damage to the Takahama wharf of Kobe port. Large inertial forces were generated in the deck, and a horizontal displacement occurred in the alluvial sand layer below the rubble mound. The horizontal displacement was 1.3–1.7 m, and the piles were inclined about 3° (PINAC, 2001). A 7.2 magnitude earthquake striking Israel in 1995 caused slope failure at the main wharf of the port of Eilat, with a joint displacement of 5–15 mm (PINAC, 2001).

Earthquake damage occurring on the pile-supported structure is generally influenced by the inertial force of the deck and the kinematic force between the soil and the piles (PIANC, 2001; Lombardi and Bhattacharya, 2016). Especially, a pile-supported wharf built on a slope encounters greater kinematic force than a similar pier built on horizontal ground due to slope failure under the impact of the earthquake. It is, therefore, necessary to evaluate the dynamic behavior of pile-supported wharf built on a slope, because the kinematic forces generated between the soil and the structure by the slope failure can cause structural damage.

Therefore, in this study, a dynamic centrifuge model tests of pile-supported wharves installed on slopes and pile-supported piers constructed on horizontal ground were conducted to analysis the dynamic behavior of the pile-supported structures due to slope failure during earthquake.

2 DYNAMIC CENTRIFUGE MODEL TESTS

A centrifuge testing machine at the KAIST Geo-Centrifuge Testing Center in Korea was used for the experiment, and a 3 × 3 section of a pile-supported structure in Pohang, South Korea (length: 2,400 mm, thickness: 0.9 m) was selected as the test model (Kim et al., 2013; Lee et al., 2013).

A simplified ground model comprising a single sand layer was installed with either a horizontal or inclined (at 33°) surface. Displacement meters, accelerometers, and strain gauges were installed as shown in Figure 1. Air-pluviated dry silica sand artificially produced by hammer crushing was adjusted to a relative density of 40% and 45%, as shown in Table 1. Each model was built at 1/48 scale, and the bending stiffness of the piles was adjusted according to the seismic load applied laterally (McCullough, 2003). Table 2 lists the properties of the scale model and prototype, and Table 3 presents the characteristics of the horizontal (HA45) and inclined (IA40) ground models.

The input wave was an artificial earthquake reflecting the characteristics of the Pohang site in Korea according to the Korean Ministry of Oceans and Fisheries Seismic design standards of harbor and port (1999), as shown in Figure 2. Four input waves were used in each model, and the experiment was performed under increasing acceleration from 0.04 to 0.23 g.

Table 1. Silica sand properties

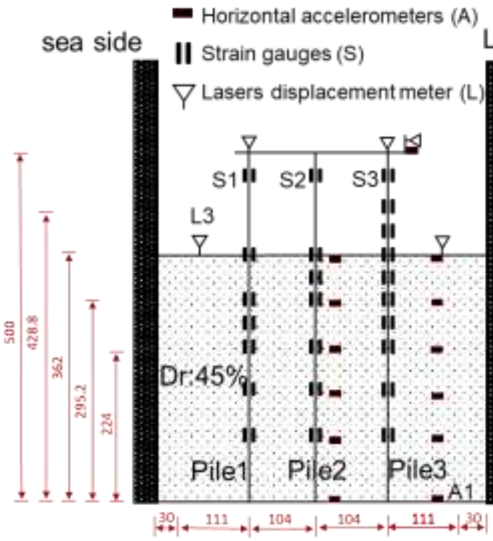
Silica sand	
USCS	SP
C_c	1.16
C_u	1.96
C_s	2.63
$\gamma_{d.max}$ (kN/m3)	16.5
$\gamma_{d.min}$ (kN/m3)	12.4

Table 2. Properties of the prototype and model (scale factor = 48)

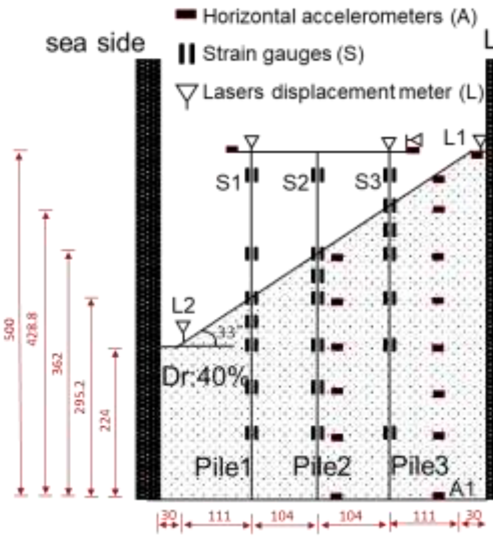
		Prototype (steel)	Model(aluminum)
Pile	Diameter (mm)	91.4	19
	Thickness (mm)	14	1
	Length (mm)	2,400	50
	Density (kN/m^3)	78.5	26.36
	Flexural rigidity (kN·m^2),	8.42x10^5	0.157
Deck	Thickness (mm)	1,000	20
	Density (kN/m^3)	24.5	26.36

Table 3. Dynamic centrifuge test models

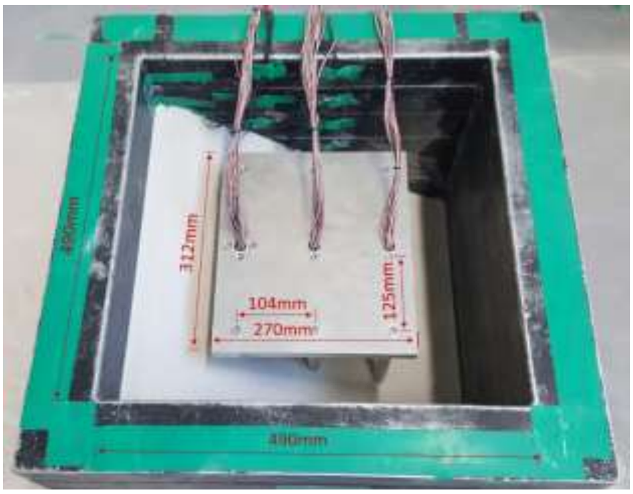
model	HA45	IA40
Ground slope(°)	Horizontal(0°)	Inclined(33°)
Input wave	Artificial wave	Artificial wave
Relative density (%)	45	40
Pile arrangement	3x3	3x3
Input PGA(g)	0.09,0.14,0.18,0.23	0.04,0.12,0.16,0.23



(a) Horizontal ground model (HA45)

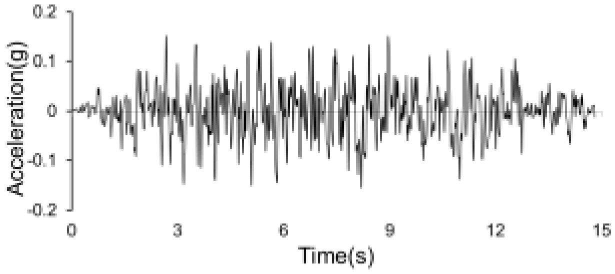


(b) Inclined ground model (IA40)

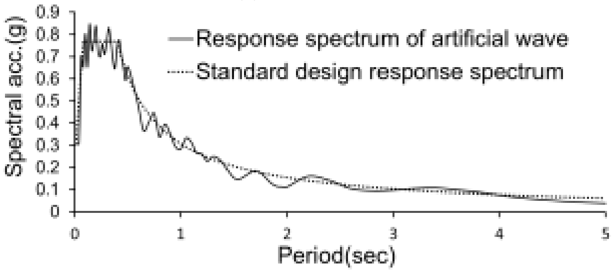


(c) Pile-supported wharf layout

Fig. 1. Dynamic centrifuge test models.



(a) Artificial wave



(b) Standard design response spectrum in Korea

Fig. 2. Input wave and standard design response spectrum.

3 RESULTS

Figure 3 shows the ground subsidence of the models. The x-axis represents the seismic acceleration applied to the bedrock, and the y-axis indicates the cumulative vertical displacement, which increases in the negative (–) direction. The labels L1, L2, and L3 indicate the displacements measured at the corresponding positions as shown in Figure 1: L1 and L2 are the upper and lower ground displacements, respectively, in the IA40 model, and L3 is the central ground displacement in the HA45 model.

As shown in Figure 3, as the input acceleration increases up to 0.12 g, the ground subsidence increases in both models. However, when the input acceleration exceeds 0.12 g, the three curves show a marked change. The sinking at L1 occurs mainly due to slope failure. Compared with the higher ground height at L2, the L3 ground displacement remains relatively constant without major change. Overall, the figure illustrates the location of slope failure. In IA40 Model, the slope failure occurred under input wave greater than 0.12 g. By contrast, the HA45 model maintained a constant ground height without collapse.

Figure 4 shows the pile moment by depth at an input acceleration of 0.23 g for the three piles in each model. As shown in Figure 4(a), the greatest moment in the ground at pile 1 is smaller and the deeper in the IA40 model than in the HA45 model. However, Figure 4(b) illustrates similar pile 2 behavior in the two models. Pile 3, in Figure 4(c), displays a larger moment in ground at a shallower depth in the IA40 model compared with the HA45 model. This result is attributed to the increased ground reaction force in the upper ground with increased soil height (see Figure 1). An increase in the maximum moment is also observed.

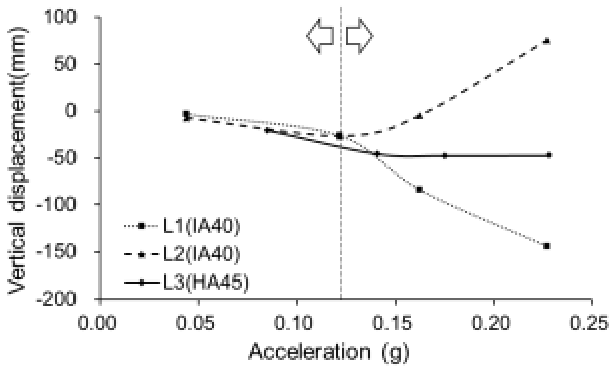
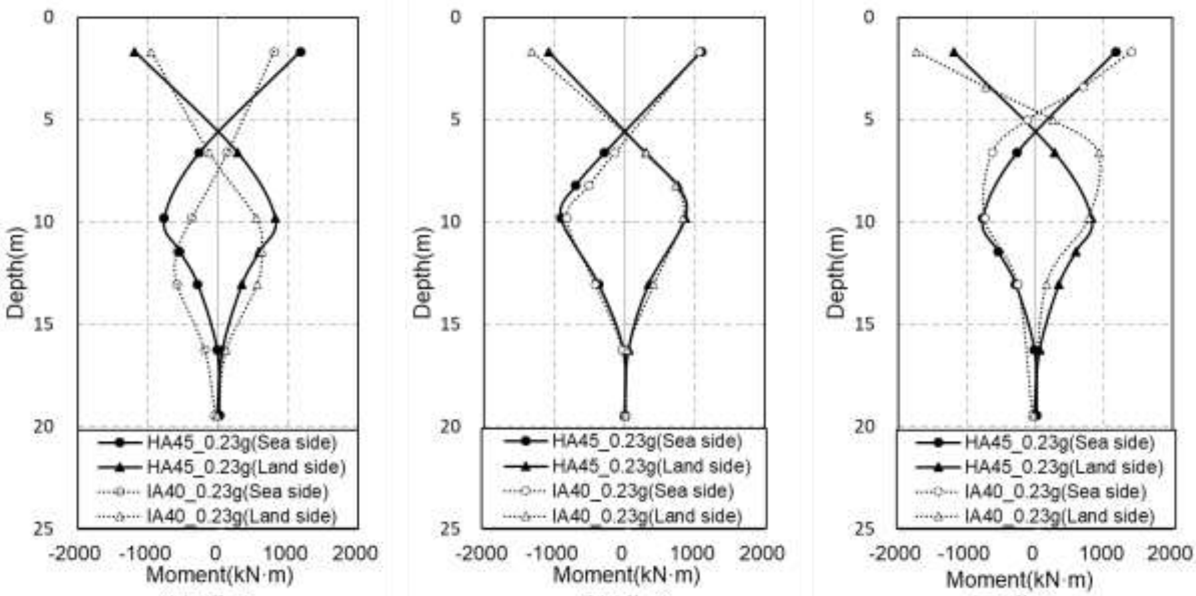


Fig. 3. Comparison of ground subsidence in the sloping (L1 and L2) and horizontal (L3) ground models

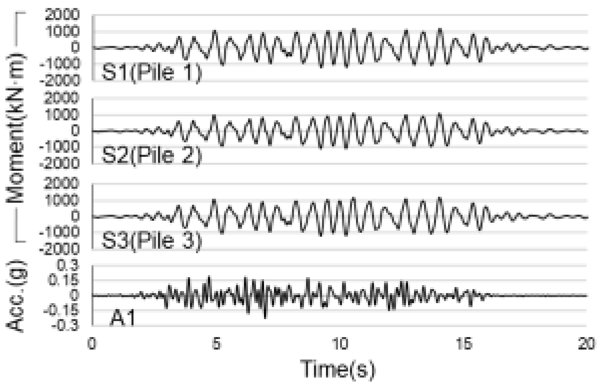


(a) Pile 1 (b) Pile 2 (c) Pile 3

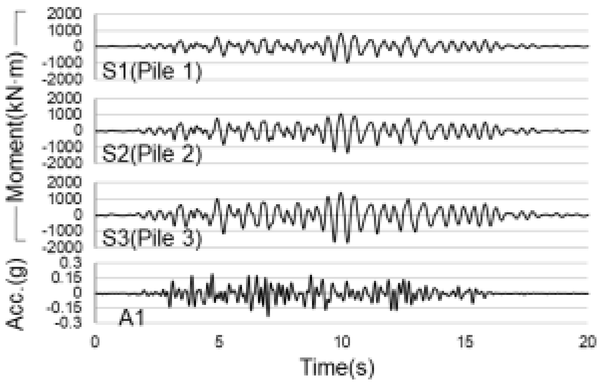
Fig. 4. Pile moment by depth (Input PGA, 0.23g)

Figure 5 illustrates the moment time history curve and acceleration time history curve of piles and base plate. S1, S2, and S3 indicate the location of the upper strain gauges of piles 1, 2, and 3, respectively, and A1 denotes the accelerometer location of base plate in Figure 1. Figure 5(a) and Figure 5(b) highlight the results of HA45 model and IA40 model, respectively. The moment time history curves appear to show almost identical shape and value, as shown in Figure 5(a). By contrast, the three figures show different moment values, as shown in Figure 5(b). The maximum moment occurred in the S3 of pile 3, and the minimum moment was found in the S1 of pile 1 in the IA40 model. The moment may be the largest in pile 3, since the largest kinematic force occurred following slope failure under tremor.

Figure 6 shows the maximum moment of the piles with respect to input acceleration. Increasing acceleration also enhances the maximum pile moment. When the input acceleration exceeds 0.12 g, the moment in the IA40 model increases to a higher value, while the HA45 model shows a constant increase in the maximum moment. As shown in Figure 3, slope failure occurs at an input acceleration greater than 0.12 g. The resulting additional kinematic force between the soil and structure greatly influences the moment of the pile.



(a) HA45 model



(b) IA40 model

Fig. 5. Moment time history curve (Input PGA, 0.23g)

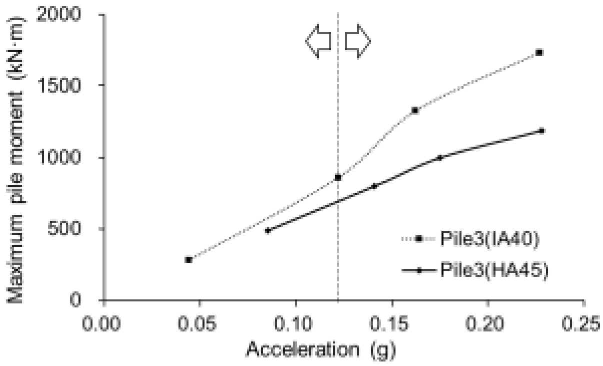


Fig. 6. Maximum moment of pile 3 in the two models.

3 CONCLUSIONS

In this study, dynamic centrifuge model tests were utilized to analyze the dynamic behavior of pile-supported structures on sloping and flat ground. Comparison of the ground displacements in the models revealed that the sloping ground started to fail at input accelerations higher than 0.12 g. The additional kinematic forces resulting from the interaction between the soil and the piles significantly increase the pile moment. These results show that the pile-supported wharf installed on a slope is strongly influenced by the kinematic force between the soil and the piles.

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