

A Study on the Improvement of Response Spectrum Analysis of Pile-supported Wharf with Dynamic Centrifuge Model Test



Jung-Won Yun

Smart City & Construction Engineering, Korea University of Science & Technology, Goyang, Gyeonggi, Republic of Korea

Jin-Tae Han

Korea Institute of Civil Engineering & Building Technology, Goyang, Gyeonggi, Republic of Korea

Seok-Jung Kim

Korea Institute of Civil Engineering & Building Technology, Goyang, Gyeonggi, Republic of Korea

Jae-Soon Choi

Seokyeong University, Seoul, Republic of Korea

ABSTRACT

As a seismic-design method for pile-supported wharves, response spectrum analysis, which can easily obtain the maximum response of a structure, is widely used. However, there is some confusion, because the ways to calculate the input ground acceleration proposed in the standards are different in the response spectrum analysis of pile-supported wharves. In this study, a dynamic centrifuge model test and response spectrum analysis were conducted to consider the seismic acceleration amplification for the seismic design of pile-supported wharves. The response spectrum analysis and dynamic centrifuge test results showed reasonable differences; the response spectrum analysis results using the amplified acceleration in the ground surface were most like the centrifuge test results.

RÉSUMÉ.

Pour un quai sur pilotis conçu selon une méthode de conception parasismique, l'analyse du spectre de réponse est souvent réalisée car elle permet d'obtenir facilement la réponse maximale d'une structure. Cependant, il existe une confusion parce que les méthodes de détermination de l'accélération au sol proposées dans les normes diffèrent par rapport à l'analyse du spectre de réponse des quais sur pilotis. Dans le cadre de l'étude, des essais sur des modèles de centrifugeuses dynamiques et des analyses du spectre de réponse ont été réalisés afin de déterminer l'amplification de l'accélération sismique pour la conception parasismique du quai sur pilotis. Il en résulte que les analyses du spectre de réponse et les résultats des tests sur les centrifugeuses montrent une différence raisonnable dans les résultats, alors que les résultats de l'analyse du spectre de réponse obtenus en utilisant l'accélération amplifiée à la surface du sol ressemblent le plus aux résultats des essais de centrifugation.

1 INTRODUCTION

For port structures, such as pile-supported wharves, it is difficult to carry out a mock-up test at actual size. Seismic performance should therefore be evaluated by carrying out a scale model test and numerical analysis. In practice, response spectrum analysis is mainly used for the seismic design of a pile-supported wharf.

Response spectrum analysis is an elastic calculation of the peak dynamic response of all significant modes of the structure, using the site-dependent design spectrum. This method has been widely used for bridges and structures, because it can consider many modes by means of the mode combination method in addition to the simplicity of analysis (Eurocode 8, 2005).

However, although it is frequently used in practice, there have been few studies on the response spectrum analysis of pile-supported wharves.

For response spectrum analysis, the input ground acceleration can be calculated by the seismic coefficient, because it is modeled only as a frame structure without modeling the ground. However, it is not appropriate to apply seismic coefficients to inclined ground, where

additional amplification occurs; so the response at the slope top may be about twice as large as at the bedrock (Ashford and Sitar, 2002; Rathje and Bray, 2001; Gazetas and Dakoulas, 1992). In addition, the standards described for the pile-supported wharf recommend using the amplified input ground acceleration by carrying out the site response analysis, but the method of finding the site response is different, which causes confusion in the response spectrum analysis of pile-supported wharves. (MLTM, 2012; PARI, 2009; PIANC, 2001; MOF, 1999).

In this study, response spectrum analysis and the dynamic centrifuge model test were carried out in order to propose a proper way to compute the input ground acceleration considering the site amplification phenomenon in the response spectrum analysis of the pile-supported wharf. First, the response spectrum analysis was carried out by obtaining the input ground acceleration at various depths of the ground by means of the dynamic centrifuge model test. Based on this, the response spectrum analysis result was compared with that of the dynamic centrifuge model test, and an appropriate way to calculate the input ground acceleration was presented.

2 INPUT GROUND ACCELERATION DETERMINATION METHOD.

The response spectrum analysis of a pile-supported wharf is a simple method, which models by frame structure without ground modeling. The MLTM (2012), PARI (2009), PIANC (2001) and MOF (1999) standards propose to model the frame structure using a virtual fixed-point technique, which is a way to find the virtual fixed point such that the pile-head reaction and pile-head bending moment become equal to the fixed-fixed beam based on the Chang (1937) method.

In order to apply the virtual fixed-point method, first, the virtual ground surface may be set at an elevation that corresponds to half the vertical distance of the slope, and the pile is designed assuming that the virtual fixed point is located at a point $1/\beta$ below the virtual ground surface. The value of β is calculated by equations (1) and (2), and is shown in Figure 1, in which k_h is the coefficient of horizontal subgrade reaction (N/cm^3), D is the pile diameter (cm), EI is the bending stiffness of the pile ($N\cdot cm$), and N is the average N-value of the ground up to the $1/\beta$ point of the ground through the standard penetration test.

$$\beta = \sqrt[4]{\frac{k_h D}{4EI}} \quad (cm^{-1}) \quad [1]$$

$$k_h = 0.15N \quad (N/cm^3) \quad [2]$$

For the response spectrum analysis of the pile-supported wharf, since the ground is not modeled, the input ground acceleration amplified by the site response analysis should be calculated. In addition, since this structure is installed on a ground layer having an inclined surface, site response analysis at a proper position is required.

MOF (1999) and PIANC (2001) propose to carry out site response analysis for response spectrum analysis and specify the input ground acceleration using a 1D equivalent linear analysis program. However, in these standards, the input ground acceleration to the surface is calculated without considering the ground slope of the pile-supported wharf. In PARI (2009), seismic responses obtained from the center of the virtual fixed point ($1/\beta$) are applied to calculate the input ground acceleration. Similarly, in MLTM (2012), seismic coefficients are obtained through the seismic response obtained from the central virtual fixed point ($1/\beta$) and are applied to the design. Figure 1 and Table 1 describe this. A uniform standard for calculating the appropriate input ground acceleration should be required.

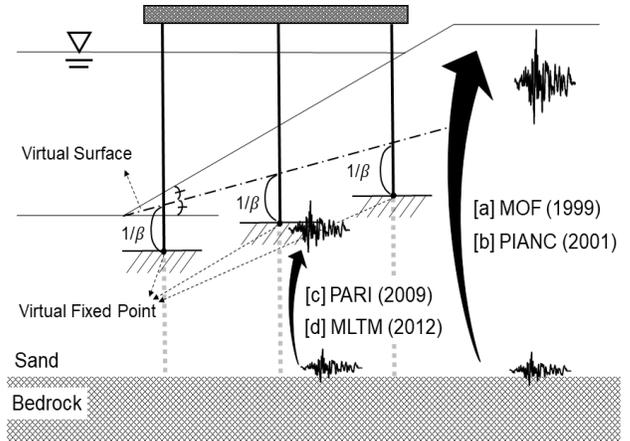


Figure 1. Calculating the input ground acceleration

Table 1. Calculating the input ground acceleration

Code	Input ground acceleration
MOF(1999)	The Peak ground acceleration(PGA) computed in the ground surface
PIANC(2001)	The computed ground surface earthquake motion parameters
PARI(2009)	The acceleration time history at the average depth of the $1/\beta$ ground point
MLTM(2012)	The response spectrum at the center of the virtual fixed point($1/\beta$)

3 DYNAMIC CENTRIFUGE TEST

The experiment was performed using a centrifuge model test machine at the KOCED Geo-Centrifuge Testing Center at KAIST. In the response spectrum analysis, the virtual fixed-point model was used, but in the centrifuge model test experiment, the entire structure was considered. The centrifuge test machine used in the experiment has a radius of rotation of 5 m and can be run under conditions of up to 240 g-ton (Kim et al., 2013).

An equivalent shear beam (ESB) model box with a length of 48 cm, a height of 49 cm, and a width of 63 cm was used in the experiment. Each layer of the box of about 6 cm was connected with a rubber buckle, which reduced the influence of the boundary effect on the soil (Kim et al., 2010).

3.1 Experiment Model

For the dynamic centrifuge model test, some sections of the publicly available pile-supported wharf piles located in Pohang, Korea, were selected. The prototype model consisted of 3x3 piles with a pile diameter of 0.914 m and a length of 24 m. The ground was simplified to sandy soil, and the slope was adjusted to 33 degrees, the same as the actual ground. The experiment models are classified into three models with different relative densities, as shown in Figure 2. Each model was constructed as a 1/48-scale model, and the flexural stiffness (EI) was controlled as in McColloug (2003) and McColloug et al. (2007). Also, as

shown in Table 2, model piles and plate were fabricated from aluminum for a reasonable simulation of flexural stiffness and section ratio. The E_p is the elastic modulus of the prototype pile, I_p is the moment of inertia of the prototype pile, E_a is the elastic modulus of the model pile, and I_a is the moment of inertia of the model pile.

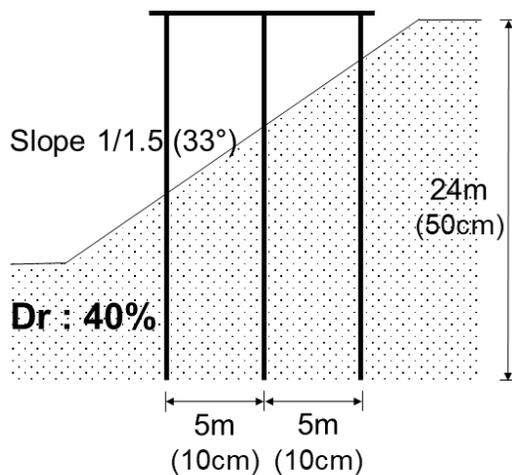
$$\frac{E_p I_p}{E_a I_a} = n^4 \quad [3]$$

3.2 Model Ground and Instrumentation

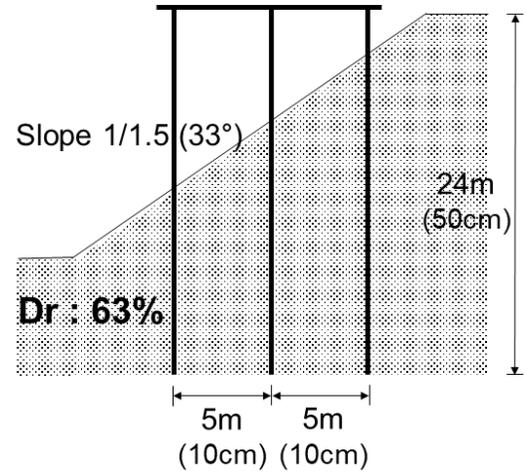
In this experiment, the silica sand artificially produced by a Hammer Crusher was used in all three models, and the basic properties of silica sand are shown in Table 3. Also, an air-pluviation method was used to control the relative density of the ground. A displacement meter, an accelerometer, and a strain gauge were used to measure the displacement of the ground, the ground acceleration, and the pile stress.

3.3 Seismic Motion

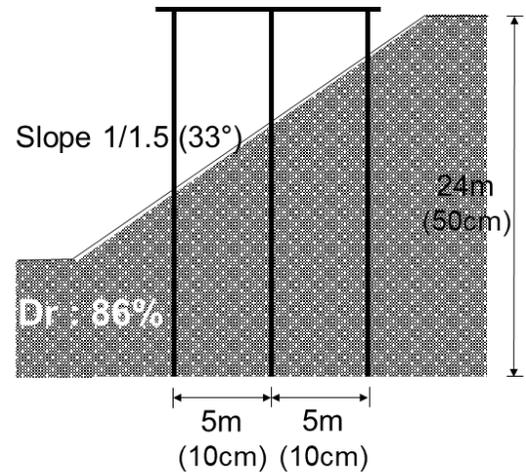
The artificial wave suitable for the Korean site proposed in the MOF (1999) standard was produced, and it can be seen that it agrees well with the standard design response spectrum shown in Figure 5. The input acceleration was applied in the range of 0.044–0.229 g at the bottom of the ESB box.



(a) Model 1 (Dr 40%)



(b) Model 2 (Dr 63%)



(c) Model 3 (Dr 86%)

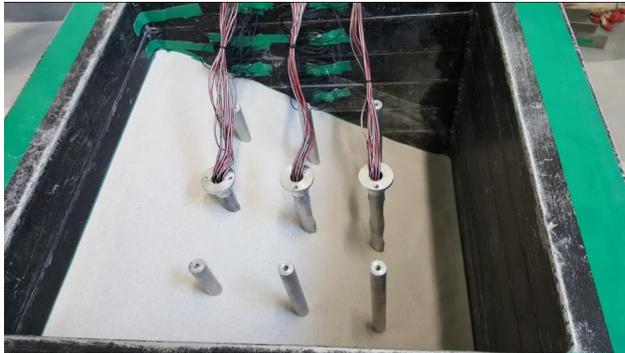
Figure 2. Geo-centrifuge model

Table 2. Properties of prototype and model (N=48)

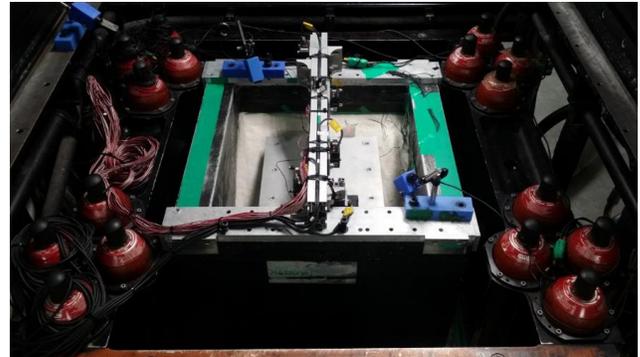
	Pile					Deck(top plate)	
	Diameter (mm)	Thickness (mm)	Length (mm)	Density (kN/m ³)	Flexural rigidity(EI) (kN · m ²)	Thickness (mm)	Density (kN/m ³)
Prototype	914	14	2,400	78.5	8.42 x10 ⁵	1,000	24.5
Model	19	1	50	26.9	1.57 x10	20	26.9

Table 3. Properties of silica sand

Soil type	USCS	C_c	C_u	C_s	$\gamma_{d,max}(kN/m^3)$	$\gamma_{d,min}(kN/m^3)$
Silica sand	SP	1.16	1.96	2.63	15.8	12.5



(a) Ground composition



(b) Dynamic centrifuge model

Figure 3. Pile supported wharf system

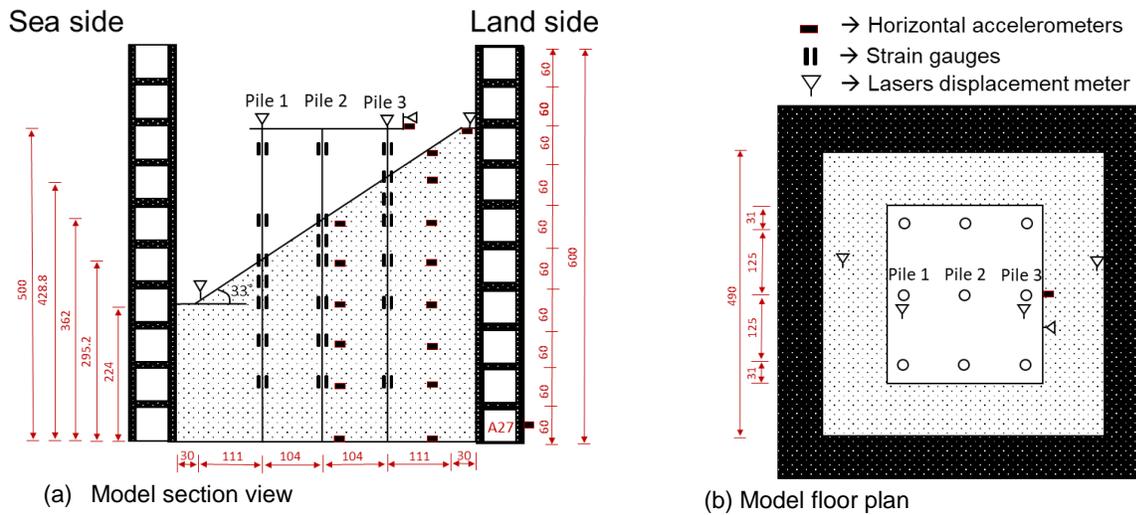
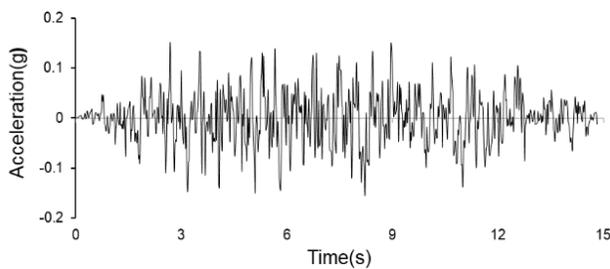
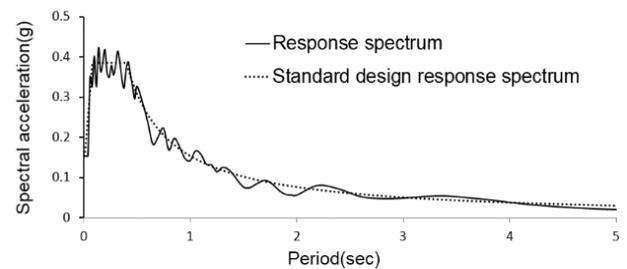


Figure 4. Model ground and instrumentation



(a) Input artificial wave



(b) Standard design response spectrum in Korea

Figure 5. Input wave

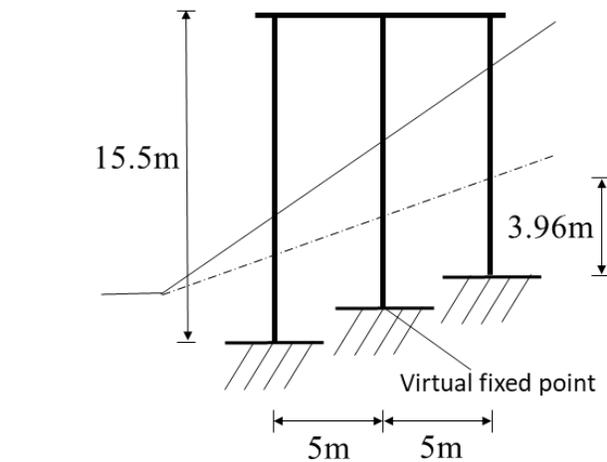
4 RESPONSE SPECTRUM ANALYSIS

The response spectrum analysis is an elastic analysis method that calculates the maximum dynamic response of all significant modes of the structure, using the site-dependent design spectrum (Eurocode 8, 2005). This method has been widely used for bridges and structures, because it can consider many modes by means of the mode combination method, in addition to the simplicity of analysis (Inoue et al., 2000; Hwang et al., 1996). Generally, Complete Quadratic Combination (CQC) is used to combine the maximum response of each mode (Wilson et al., 1981).

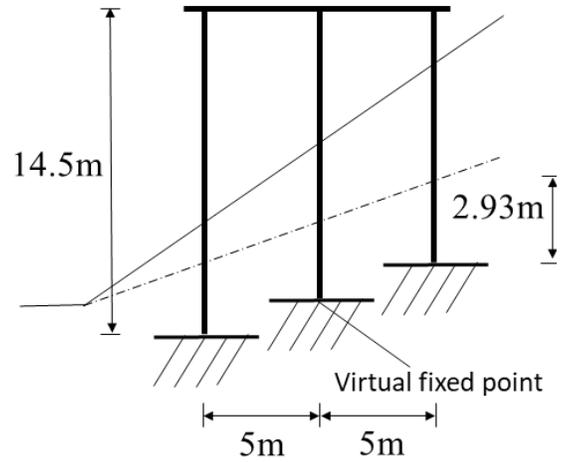
For the response spectrum analysis, because the frame structure should be designed without the ground composition, the virtual fixed-point position should be calculated as described in chapter 2 (MLTM, 2012; PARI, 2009; PIANC, 2001; MOF, 1999).

For this, the relationship between the relative density and the N-value suggested by Meyerhof (1956) is used, and the virtual fixed model is chosen as shown in Figure 6. The same property values as those of the prototype structure were applied to the response spectrum analysis, as shown in Table 2.

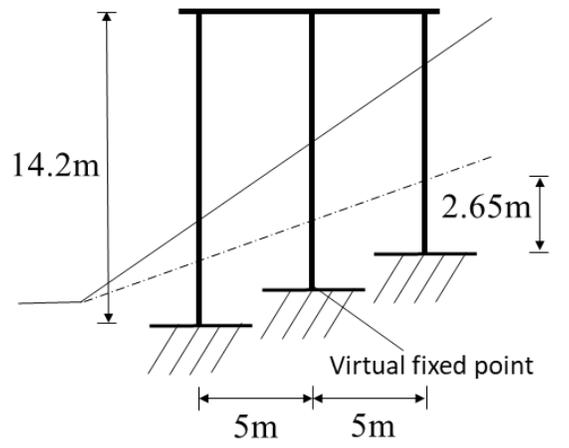
Then, the accelerations of the depths estimated by the dynamic centrifuge model test are converted into a response spectrum curve. Next, the response spectrum analysis was carried out by applying these accelerations to the virtual fixed-point model. For the analysis, the finite element analysis program MIDAS GEN 2016 ver. 1.4 was used (Midas, I. T., 2015).



(a) Model 1 (Dr 40%)



(b) Model 2 (Dr 63%)



(c) Model 3 (Dr 86%)

Figure 6. Response spectrum analysis model

Because the response spectrum analysis is an elastic analysis method, the moment can be overestimated compared to the case where actual plastic deformation occurs. Therefore, the overestimated moment should be divided by the ductility factor. However, in this study, since all models met serviceable criteria according to PIANC (2001), the moment was evaluated using the ductility factor as 1.

Table 4. Ductility factor (PIANC, 2001)

Damage state	Degree I, serviceable	Degree II, repairable	Degree III, near collapse
Pile (Peak response)	Essentially elastic response with minor or no residual deformation	Controlled limited inelastic ductile response and residual deformation intending to keep the structure repairable	Ductile response near collapse(double plastic hinge may occur at one or limited number of piles)
μ_d value	$\mu_d = 1$	$\mu_d = \frac{(1+d_u/d_y)}{2}$	$\mu_d = d_u/d_y$

5 RESULTS

In this study, the response spectrum analysis and the dynamic centrifuge model test were carried out, and a proper way to calculate the input ground acceleration was proposed by comparing analysis and experiment. As described above, the response spectrum analysis is a simple way to design a virtual fixed point without ground modeling. The virtual fixed-point method currently in use establishes the virtual fixed point such that the pile-head reaction and pile-head bending moment become equal to the fixed-fixed beam based on the Chang (1937) method. Therefore, in this study, the maximum bending moments obtained from the response spectrum analysis and the dynamic centrifuge model test were compared and evaluated.

First, Figure 7 shows the pile moment by depth for the analysis and experiment results, and an input acceleration 0.165 g model (Model 3) is selected as the representative model. Figure 7 (a) shows the dynamic centrifuge model test results with 0.165 g acceleration applied at the bottom of the ESB box, and Figure 7 (b) shows the response spectrum analysis results using the input ground acceleration amplified at the ground surface.

As shown in Figure 7 (a), the maximum moment value occurs at the top of the pile, and it decreases as downward. The minimum moment value occurs below the surface of the ground and converges to zero going downward. Comparing Pile 1 to Pile 3, the maximum moment occurs at Pile 3 (land side), because the ground is the highest at Pile 3 (land side), and the greatest kinematic force occurs by lateral deformation.

Also, as shown in Figure 7 (b), the maximum moment value occurs at the top of the pile and decreases going downward, and the minimum moment value occurs at a depth of about 10 to 14 m. Comparing Pile 1 to Pile 3, the maximum moment occurs at Pile 3 (land side), as in Figure 7 (a). In general, it is difficult to completely simulate the actual motion, because the response spectrum analysis is an elastic analysis. However, it can be seen that the pile moment characteristics are reflected to a certain depth in spite of the difference between the analysis and the experiment.

Figure 8 shows the peak ground acceleration (PGA) for each depth derived from the dynamic centrifuge model test. Nine acceleration values were measured for each depth. A01 represents the bedrock acceleration position, A04 represents the position near the virtual fixed point, and A09 represents the ground surface acceleration position. Following PARI (2009) and MLTM (2012), response spectrum analysis was carried out using the acceleration result of the A04 position, corresponding to the center of the virtual fixed point ($1/\beta$). In MOF (1999) and PIANC (2001), the response spectrum analysis was carried out using the acceleration results at the A09 position, corresponding to the ground surface.

Therefore, in this study, the response spectrum analysis was carried out using the A04 and A09 input ground acceleration presented in the standards; the maximum pile moments calculated by the response

spectrum analysis and the dynamic centrifuge model test were compared.

First, Figure 9 show the maximum moment results of the response spectrum analysis and the dynamic centrifuge model test using the input ground acceleration of the center near the virtual fixed point (A04) proposed by the PARI (2009) and MLTM (2012) standards. (a)~(c) show the maximum moments obtained at relative densities of 40%, 63%, and 86%, and the input ground acceleration was applied in the range from 0.044 to 0.229 g for analysis and experiment. The graph shows that the response spectrum analysis using the input ground acceleration of the virtual fixed-point position (A04) has much smaller moment results than in the dynamic centrifuge model.

Figure 10 shows the maximum moment results of the response spectrum analysis and the dynamic centrifuge model test using the input ground acceleration of the surface of the ground (A09) proposed by the MOF (1999) and PIANC (2001) standards. From this graph, when the response spectrum analysis is carried out by applying the acceleration of the position of the ground surface position (A09), it is similar to the moment results of the dynamic centrifuge model test.

However, even in the moment results of the dynamic centrifuge model test and of the response spectrum analysis using the input ground acceleration at the surface of the ground, the two results do not coincide exactly, because the response spectrum analysis shows elastic behavior, but, in the dynamic centrifuge model test, a slight plastic deformation occurs, even though it is within the elastic range. Also, there seems to be a large difference of the natural period between the response spectrum analysis and the dynamic centrifuge model test.

As a result, when the response spectrum analysis is carried out based on the PARI (2009) and MLTM (2012) standards, the moment results can be underestimated; hence it is appropriate to carry out the response spectrum analysis by applying the amplified acceleration of the ground surface (A09) based on the MOF (1999) and PIANC (2001) standards.

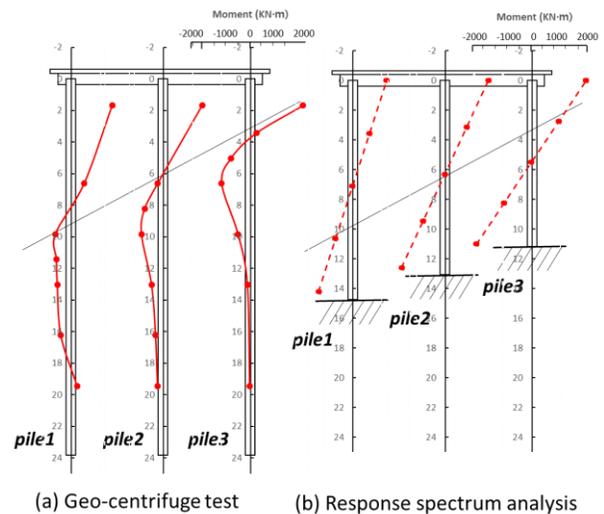


Figure 7. Pile maximum moment by depth

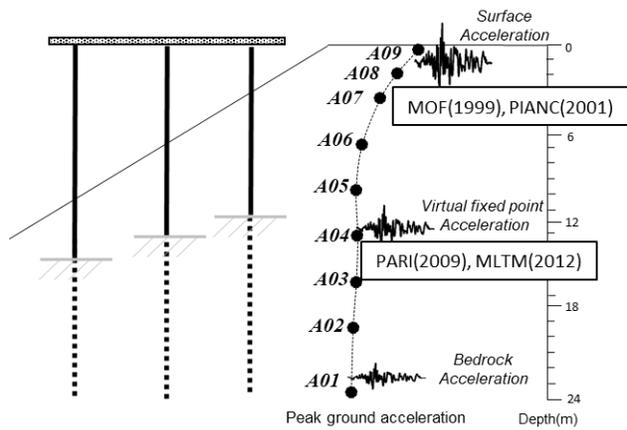
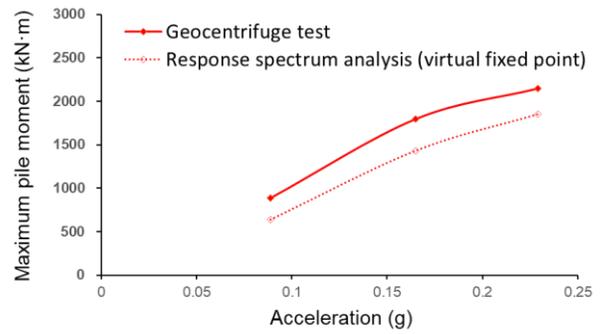
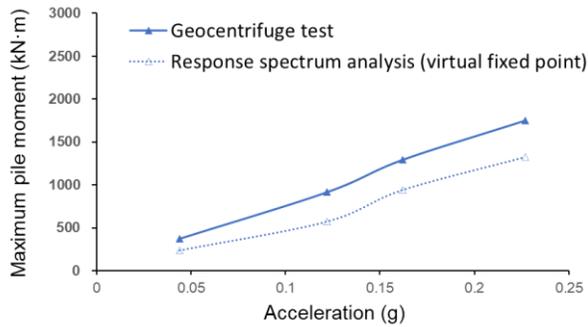


Figure 8. Calculation of input ground acceleration

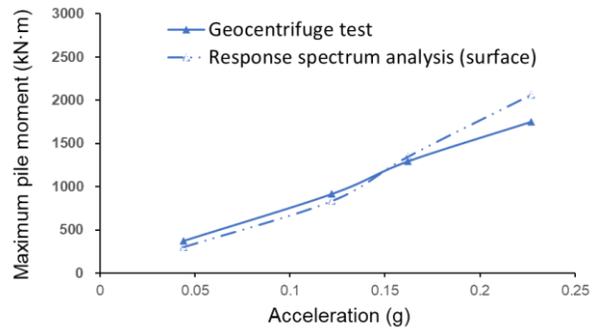


(c) Model 3 (Dr 86%)

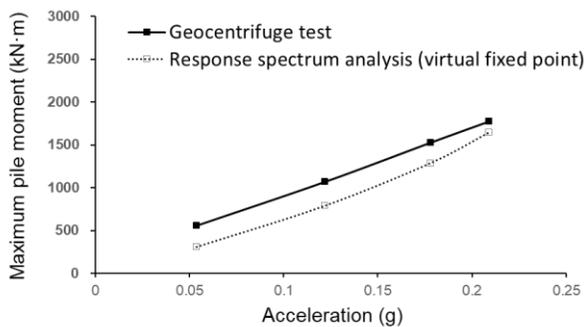
Figure 9. Geo-centrifuge test and response spectrum analysis results (Input acceleration at the virtual fixed point in the center) (PARI (2009), MLTM (2012)).



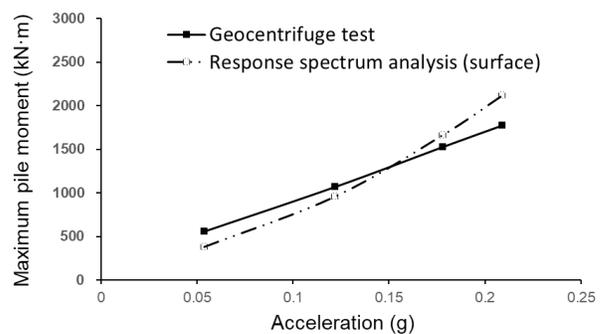
(a) Model 1 (Dr 40%)



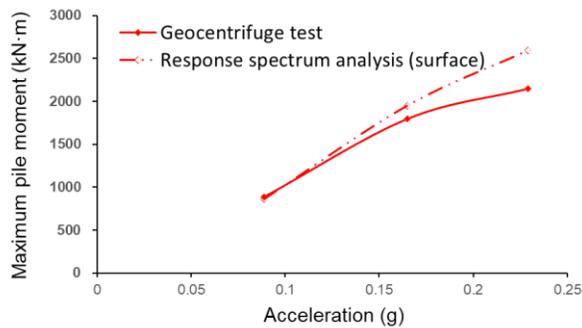
(a) Model 1 (Dr 40%)



(b) Model 2 (Dr 63%)



(b) Model 2 (Dr 63%)



(c) Model 3 (Dr 86%)

Figure 10. Geo-centrifuge test and response spectrum analysis results (Input acceleration at the ground surface) (MOF (1999), PIANC (2001)).

6 CONCLUSIONS

In this study, the response spectrum analysis and the dynamic centrifuge model test were carried out, and a proper way to calculate the input ground acceleration was proposed by comparing analysis and experiment

- (1) The pile moments by the depth from the response spectrum and geo-centrifuge test showed that the pile moment characteristics are reflected to a certain depth in spite of the difference between the analysis and the experiment.
- (2) It can be underestimated that the moment results from the response spectrum analysis by applying amplified acceleration of the virtual fixed point based on the PARI (2009) and MLTM(2012) standards.
- (3) Therefore, it seems appropriate to carry out the response spectrum analysis by applying the amplified acceleration of the ground surface based on the MOF (1999) and PIANC (2001) standards.

7. ACKNOWLEDGEMENT

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