A Study on the Development of a Performance-based Seismic Design for the Pile-supported Wharfs in South Korea

Une étude sur l'élaboration d'une conception sismique axée sur la performance des quais sur pilotis en Corée du Sud

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ABSTRACT: With regard to the seismic design of the pile-supported wharfs in South Korea, the Ministry of Land, Infrastructure, and Transport established the Seismic Performance Standard for Structures in 1997, and the standard has been applied up to the present time. Until now, however, the concrete performance-based seismic design criteria for pile-supported wharfs have not been clearly established, and the existing seismic design technology is inadequate for coping with frequent earthquakes. Therefore, in this study, the seismic performance grade and seismic performance criteria of the pile-supported wharfs in South Korea were subdivided to propose a performance-based seismic design process. In addition, a three-dimensional time history analysis of a pile-supported wharf was carried out using the data from the magnitude 5.8 earthquake that occurred in Gyeongju, South Korea on September 12, 2016 and from the created artificial earthquake that reflected the characteristics of the selected earthquake site in South Korea. Based on the seismic design standard for the existing pile-supported wharfs in South Korea, the stability of such wharfs during an earthquake was examined.

RÉSUMÉ: En ce qui concerne la conception sismique des quais sur pilotis en Corée du Sud, le Ministère du Territoire, de l'Infrastructure et des Transports a établi une Norme de performance sismique pour les structures en 1997 et la norme est appliquée jusqu'à ce jour. Jusqu'à présent, les critères de conception sismique axée sur la performance des quais sur pilotis n'ont pas été clairement établis et la technologie de conception sismique existante est inadéquate pour faire face aux séismes fréquents. Par conséquent, au cours de cette étude, la performance sismique et les critères de performance sismique des quais sur pilotis en Corée du Sud ont été subdivisés afin de proposer un processus de conception sismique axée sur la performance. En outre, une analyse tridimensionnelle (3D) d'un quai sur pilotis a été réalisée à partir des données du séisme de magnitude 5,8 survenu à Gyeongju (Corée du Sud) le 12 septembre 2016 et du tremblement de terre artificiel créé qui reflétait les caractéristiques du lieu du séisme sélectionné en Corée du Sud. Sur la base de la norme de conception sismique du quai sur pilotis existant en Corée du Sud, la stabilité de tels quais lors d'un tremblement de terre a été examinée.

KEYWORDS: Performance-based seismic design method, pile-supported wharf, time history analysis

1 INTRODUCTION

As earthquakes have been occurring frequently throughout the world of late, the awareness of the importance of seismic design for port structures has also increased. Therefore, a shift has been seen from the conventionally applied allowable-stress design method (ASD) and ultimate-strength design method (USD) to the performance-based seismic design method (PBD), which can produce a flexible design.

Performance-based seismic design is a design method that enables designers to design more flexibly, unlike with the existing design method. This method can enable designers to produce a reasonable and economical design by adjusting the seismic performance criteria according to the importance of the structure to be designed. The method can also be applied to port structures, as proposed by the International Navigation Association PIANC (2001), Japan PARI (2009), U.S. ASCE and COPRI (2014).

At present, in South Korea, the structures are designed according to only two seismic performance criteria. Based on the design standards and the latest research trends of the countries with advanced seismic design methods, points for improvement have been presented with regard to the seismic performance criteria, design seismic acceleration, and earthquake risk map. In South Korea, however, most of the previous studies conducted performance-based design for geotechnical and port structures, and there have been insufficient detailed studies on the performance-based design of pile-supported wharfs. In addition, the proper classification system of the seismic performance criteria is inadequate for preparing against powerful earthquakes, such as the magnitude 5.8 earthquake that occurred in Gyeongju, South Korea on September 12, 2016.

Therefore, in this study, the seismic performance grade and seismic performance criteria of the pile-supported wharfs in South Korea were subdivided to propose a performance-based seismic design process and proper seismic design criteria. In addition, a three-dimensional time history analysis of a pile-supported wharf was carried out using the data from the magnitude 5.8 earthquake that occurred in Gyeongju, South Korea on September 12, 2016 and from the created artificial earthquake that reflected the characteristics of the selected earthquake site in South Korea. Based on the seismic design standard for the existing pile-supported wharfs in South Korea, the stability of such wharfs during an earthquake was examined.

2 CURRENT STATUS OF THE SEISMIC DESIGN OF PILE-SUPPORTED WHARFS

2.1 *Performance-based seismic design method in South Korea*

The seismic performance grade of pile-supported wharfs in the Port and Harbor Design Standard (2014) includes seismic grades 1 and 2. Grade 1 structures are those that are bound to entail much loss of life and property when a powerful earthquake occurs, where earthquake disaster recovery is important, and that are classified based on the country's national defense needs. Grade 2 structures, on the other hand, are other general port structures.

The seismic design of a structure is determined by the performance grade and performance level and is shown as 50, 100, 500, and 1,000 years according to the average reproduction cycle. The seismic performance criteria of port structures are the collapse prevention level and the serviceability level. The serviceability level refers to the level of a structure's capability to sustain its normal function during or even after an earthquake, without incurring serious structural damage. The collapse prevention level, on the other hand, refers to the level of capability of a structure that incurred limited structural damage due to an earthquake to resume its function as a port structure after a short time, after emergency repair. Port structures should be designed to have high collapse prevention and serviceability levels.

2.2 *Overseas performance-based seismic design methods*

PIANC (2001), which is widely used in seismic design, determines the displacement and stress damage criteria of a pile-supported wharf, and defines the seismic performance criteria according to the degree of damage. The seismic performance grades of structures are S, A, B, and C, with S applying to critical structures that are likely to cause casualties and incur massive damages.

The seismic design of a structure is designated as Level 1 (L1) or Level 2 (L2). Level 1 earthquake motion (L1) is typically defined as motion with a 50% probability of exceedance during the life span of a structure, and Level 2 earthquake motion (L2) is typically defined as motion with a 10% probability of exceedance during a structure's life span.

3 PROPOSED PERFORMANCE-BASED DESIGN PROCESS FOR PILE-SUPPORTED WHARFS

3.1 *Determination of the seismic performance grade and seismic design method of a structure*

The seismic design methods for pile-supported wharfs that have been applied in South Korea consist of three types: the single-mode spectrum method (equivalent static analysis method), the multi-mode spectrum method, and the time history analysis method. Among them, the time history analysis method is applied when accurate seismic performance evaluation of a structure is required. In the design standard currently being used in South Korea, the single-mode spectrum method (response spectrum method) is proposed as the standard design method for seismic-performance grade 2 structures. Considering, however, that the multi-mode spectrum method is applied in most seismic design cases in South Korea, it is reasonable to propose such method (response spectrum method) as the standard seismic design method for seismic-performance grade 2 structures. The single-mode spectrum method, however, can be used for preliminary design purposes. Also, in the existing design standard, it is proposed that both elastic and inelastic analyses be used in time history analysis. When evaluating the quantitative seismic performance of the pile foundation, however, it is necessary to apply the time history analysis method (inelastic analysis), which can simulate the material nonlinear behavior (plastic behavior) of the pile and the ground.

Therefore, it is proposed in this study that the single-mode spectrum method (equivalent static analysis method) be applied as the preliminary design method for seismic-performance grade 2 structures, and that the multi-mode spectrum method be applied as the standard design method for such structures. At this time, seismic-performance grade 1 (seismic reinforcement) applies when enhanced seismic performance evaluation of a structure is required. It is proposed that the single-mode spectrum method be applied as the preliminary design method for seismic-performance grade 1 and seismic-performance grade 1 (seismic reinforcement) structures, that the section be determined using the multi-mode spectrum method, and that the time history analysis method (inelastic analysis) then be applied to verify if the seismic performance criteria have been satisfied. In other words, the multi-mode spectrum and time history analysis methods are proposed as the standard design methods for seismic-performance grade 1 and seismic-performance grade 1 (seismic reinforcement) structures. Table 1 shows the aforementioned design methods.

Table 1. Design method application

Design method	Proposed performance grade		
	Grade 2	Grade 1	Grade 1 (seismic reinforcement)
Single-mode spectrum analysis method	░	░	░
Multi-mode spectrum analysis method	■	■	■
Time history analysis method (inelastic)		■	■

░ : Preliminary design ■ : Main design

3.2 *Determination of seismic performance criteria*

The present seismic performance criteria of the pile-supported wharfs in South Korea are the serviceability level and the collapse prevention level. In South Korea, as the seismic performance criteria are not detailed, they are defined by applying the PIANC (2001) standard, as shown in Table 2.

Table 2. Determination of seismic performance criteria

Performance grade (PIANC, 2001)	Proposed performance grade	Design earthquake	
		Level 1 (L1)	Level 1 (L2)
Grade S	Grade 1 (seismic reinforcement)	Degree I: Serviceable	Degree I: Serviceable
Grade A	Grade 1	Degree I: Serviceable	Degree II: Repairable
Grade B	Grade 2	Degree I: Serviceable	Degree III: Near collapse
Grade C		Degree II: Repairable	Degree IV: Collapse

3.3 *Determination of damage criteria*

For the damage criteria of pile-supported wharfs, PIANC (2001) proposes Level I to Level IV as the seismic design criteria, as shown in Table 3.

Table 3. Proposed damage criteria (PIANC, 2001)

Level of damage	Residual displacement		Peak response
	Differential settlement between the deck and the land behind	Residual tilting towards the sea	Pile*
Degree I	Less than 0.1-0.3 m	Less than 2-3°	Essentially elastic response with minor or no residual deformation
Degree II	N/A	N/A	Controlled limited inelastic ductile response and residual deformation intending to keep the structure repairable
Degree III	N/A	N/A	Ductile response near collapse (double plastic hinge may occur at only one pile or at a limited number of piles)
Degree IV	N/A	N/A	Beyond the state of Degree III

*Bending failure should precede shear failure in structural components.

4. TIME HISTORY ANALYSIS OF PILE-SUPPORTED WHARFS FOR SAFETY ASSESSMENT

3D time history analysis of a pile-supported wharf was carried out using the data from the magnitude 5.8 earthquake that occurred in Gyeongju, South Korea on September 12, 2016 and from the created artificial earthquake that reflected the characteristics of the selected earthquake site in South Korea. Based on the seismic design standard for the existing pile-supported wharfs, the stability of the pile-supported wharfs in South Korea during an earthquake was examined.

4.1 *Analysis conditions*

For the time history analysis of a pile-supported wharf considering the ground, the PLAXIS 3D ver.1.0.0 program was used. PLAXIS 3D is a 3D FEM program that is widely used in the world today mainly for ground-based analysis such as for tunnels, slopes, and others. The PLAXIS 3D model consists of a 3D triangular mesh, as shown in Figure 1, and the contact element between the pile and the ground was determined using the documents of Goodman et al. (1968) and Van Langen and Vermeer (1991) as references. In this analysis, the elastoplastic Mohr-Coulomb model was used for the ground.

In the case of the standard cross-section, a section of a pile-supported wharf (2x3 piles) was selected from the wharf construction site located in Pohang, South Korea. The distance between the piles is 5 m wide and 6 m high. To simplify the analysis ground and the property values, the ground was divided into the sand and bedrock layers. For the shear wave velocity, an appropriate value in accordance with Seismic Design Standard of Ports and Harbors in South Korea (1999) was applied. The shear wave velocity of the sand layer was 270 m/s, and that of the soft rock layer was 1100 m/s. The models and properties that were used in the analysis are shown in Figure 1 and Table 4.

In the case of the standard design response spectrum, a 1,000-year-return-period earthquake with seismic-performance grade 1 and a collapse prevention level wave was used. The maximum acceleration of the seismic wave with regard to the 1,000-year earthquake ground motion was determined to be 0.154 g by referring to the Port and Harbor Design Standard (2014).

In the case of the Gyeongju earthquake, the seismic value (E-W) of the USN Observatory, which is the largest value observed among the 3 seismic values (MKL, USN and DKJ) was used. As shown in Figure 2(b), the maximum acceleration has a 0.24 g value, which is larger than 0.154 g, the maximum acceleration value of the seismic wave generated by the standard design response spectrum.

Figure 3 shows the results of the comparison of the Gyeongju seismic wave and the artificial seismic wave produced with the standard design response spectrum in South Korea. It can be seen that the acceleration value of the artificial seismic wave is almost similar to that of the standard design response spectrum. In the case of the Gyeongju seismic wave, they had a large acceleration value in the short-period region, and a small acceleration value in the long-period region, compared with the standard design response spectrum.

4.2 *Comparison of analysis results*

In this section, the results of the time history analysis of a pile-supported wharf that was carried out using the Gyeongju seismic wave in South Korea and the created artificial earthquake that reflected the characteristics of the selected earthquake site in South Korea are presented. Based on the seismic design standard of the existing pile-supported wharfs in South Korea, the stability of such wharfs during an earthquake was examined.

The results of the two aforementioned analyses were compared through time history analysis. In both analyses, it was found that the displacement increased sharply between 3 and 5 seconds, and showed the maximum value, after which the displacement converged to an almost constant value. Both analyses showed a similar tendency, but the maximum displacement of the artificial seismic wave was 6.3 cm while that of the Gyeongju seismic wave was 2.3 cm. The maximum displacement of the artificial seismic wave was thus larger than that of the Gyeongju seismic wave. It is predicted that the maximum acceleration value of the Gyeongju seismic wave is larger, but it does not affect the ground because the waves\ are mostly short-period component seismic wave. On the other hand, in the case of the artificial seismic wave, the maximum acceleration value is smaller, but the long-term and short-period components are widely distributed from 1 to 10 Hz, and as such, the maximum displacement value is larger.

In MOF, the maximum horizontal displacement is 10 cm for the serviceability level and 30 cm for the collapse prevention level as shown in Figure 4 and Table 5. This analysis was based on the 30 cm standard because time history analysis had been carried out at the collapse prevention level. In both analyses, the maximum displacement values met the previously proposed criteria.

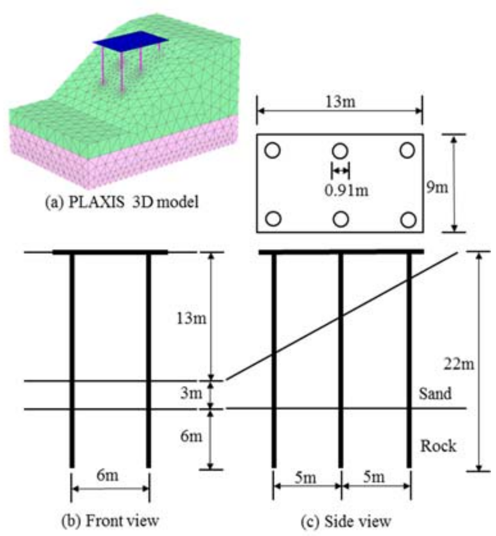

Figure 1. PLAXIS 3D model.

Table 4. Material profile for numerical analysis

Property	c kN/m^2	Φ	γ kN/m^3	γ_{sat} kN/m^3	E kN/m^3	υ
Soil (sand)	0	35	18	20	3.59E5	0.34
Rock	1000	40	25	25	7.59E6	0.23
Plate (concrete)	D=1 m		24.5		2.6E7	0.16
Pile (steel)	A=0.03958 m^2 γ = 78.5			D=0.914 m t=0.014 m E = 2.1E8		

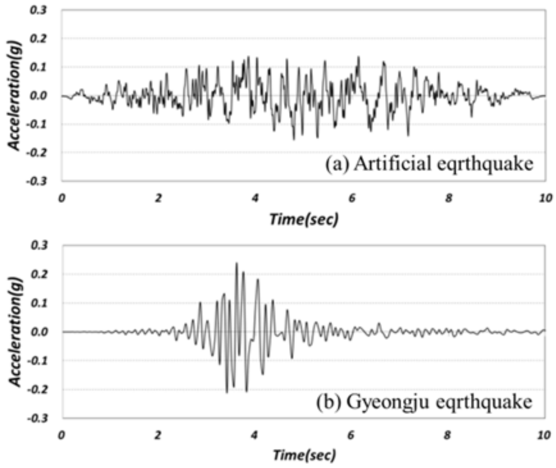

Figure 2. Artificial and Gyeongju earthquakes.

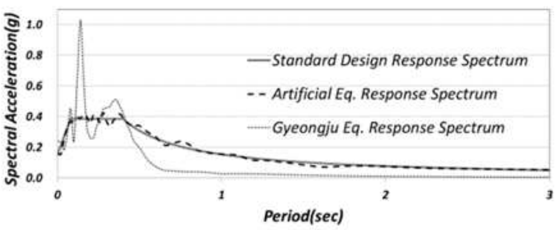

Figure 3. Response spectrum curve.

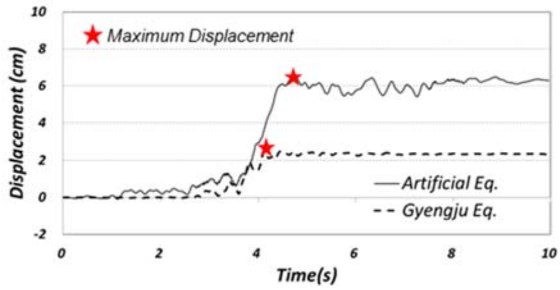

Figure 4. Pile displacement.

Table 5. Comparison of pile displacement

Seismic waves	Maximum displacement criteria		Result
	Collapse prevention level	Serviceability level	
	30 cm	10 cm	
Artificial wave	6.57 cm	-	OK
Gyeongju wave	2.52 cm	-	OK

5 CONCLUSIONS

In this study, the seismic performance grade and seismic performance criteria of the pile-supported wharfs in South Korea were subdivided to develop a performance-based seismic design method for pile-supported wharfs, and proper seismic performance criteria were proposed by referring to the documents of PIANC (2001). In addition, three-dimensional (3D) time history analysis was carried out using the data from the magnitude 5.8 earthquake that occurred in Gyeongju, South Korea on September 12, 2016 and from the created artificial earthquake that reflected the characteristics of the selected earthquake site in South Korea, to evaluate the stability of the pile-supported wharfs in South Korea during an earthquake.

(1) To subdivide the seismic performance grade of a pile-support wharf, the existing two seismic performance grades (grades 1 and 2) were classified into three categories (grade 1 (seismic reinforcement), grade 1, and grade 2), and the seismic performance criteria were classified into four categories.
(2) For the seismic performance grades, the single-mode spectrum method (equivalent static analysis method) was applied as a preliminary design method. The seismic-performance grade 2 structures were determined using the multi-mode spectrum method while the seismic-performance grade 1 and seismic-performance grade 1 (seismic reinforcement) structures were determined using the time history analysis method. In addition, a procedure for satisfying the seismic performance criteria was proposed.
(3) In the case of the response spectrum curve of the seismic wave, the Gyeongju seismic wave had a large maximum acceleration value in the short-period region and a small maximum acceleration value in the long-period region compared with the standard design response spectrum.
(4) The comparison of the two results of the time history analysis revealed that the maximum displacement of the artificial seismic wave was larger because the Gyeongju seismic wave were composed of short-period seismic wave and thus did not greatly influence the ground. Both analyses showed that the maximum displacement values met the 30 cm standard for preventing collapse.

6. ACKNOWLEDGEMENT

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