Physical Modelling in Geotechnics

Modelling the behaviour of gravity-type quay wall during the 2017 Pohang earthquake

M.G. Lee
Earthquake Research Center, KIGAM, Daejeon, Korea

H.J. Park
Department of Civil Engineering, Seoul Nat'l Univ. of Science and Technology, Seoul, Korea

J.S. Lee
Department of Civil and Environmental Engineering, Wonkwang University, Iksan, Korea

ABSTRACT: The performance verification process that quantitatively evaluates whether the seismic performance of the designed quay wall for the design earthquake is within the allowable permanent displacement set for each target performance level of the quay wall is very important for the performance-based seismic design of gravity-type quay walls. Therefore, a performance verification method that can comprehensively consider the excess pore pressure buildup and soil nonlinear behaviour and soil-structure interaction in response to an earthquake is required to quantitatively evaluate the seismic performance of the quay wall. Recently, various seismic design codes adopting the performance-based seismic design concept have recommended centrifuge testing as a representative seismic performance verification method along with numerical nonlinear effective stress analysis. In this study, to evaluate the reliability of centrifuge testing as a seismic performance verification method of the gravity-type quay wall, a centrifuge modelling for the damaged gravity-type quay wall in Youngil Bay Port during the Pohang earthquake in 2017 was performed. The measured records of the model were similar to the actual records of the damaged wall.

Keywords: dynamic centrifuge test, gravity-type quay wall, frequency, excess pore pressure.

1 INTRODUCTION

Conventional simplified analysis methods for seismic design of gravity-type quay wall are based on providing capacity to resist a design seismic force, but they do not provide information on the performance of a structure when the limit of the force-balance is exceeded (Lee et al., 2019b). Since the Great Hanshin Earthquake-damaged Kobe Port in 1995, significant advances have been made in dynamic analysis, which can comprehensively consider soil–structure interaction and soil nonlinear behavior in response to an earthquake, and performance-based design has been introduced for port structures (Lee et al., 2021).

Centrifuge tests rotate a scaled model at high speed with a centrifugal acceleration far higher than that of gravity and can be used to simulate in situ stress conditions in soil models. They have been used in many prior studies to supplement the lack of recorded case histories to validate the reliability of existing design methods and develop seismic design techniques for port structures. Several performance-based seismic design codes for port structures have recently recommended centrifuge testing as a seismic performance verification method along with numerical nonlinear effective stress analysis (Lee et al., 2021).

In this study, a centrifuge test simulating the performance of a gravity-type quay wall in Youngil Bay Port damaged during the Pohang earthquake in 2017 was performed and also compared with actual records of the damaged wall (MOF, 2018) to evaluate the reliability of centrifuge test as a seismic performance verification method of the gravity-type quay wall.

2 BENCHMARK CASE HISTORY: YOUNGIL BAY PORT QUAY WALL

A moment magnitude (M) 5.4 earthquake occurred in Pohang City in the southeastern part of the Korean peninsula on 15 November 2017, and lateral spreading took place at a gravity-type quay wall in Youngil Bay Port approximately 6 km away from the main shock epicenter (Lee et al., 2021; MOF, 2018). Figure 1 shows the cross-section of the gravity type quay wall of the Youngil Bay Port damaged during the Pohang earthquake, which is a simulated object of this test. The total weight corresponding to the simulated range of the target quay wall containing internal filling materials and compartments is 3753 tons. The rubble mound and stone backfill were respectively located beneath and backside of the quay wall, and the backfill area was filled with weathered granite soil. In addition, the quantitative damage information of the quay wall at Youngil Bay Port during the Pohang earthquake was summarized in Table 1.

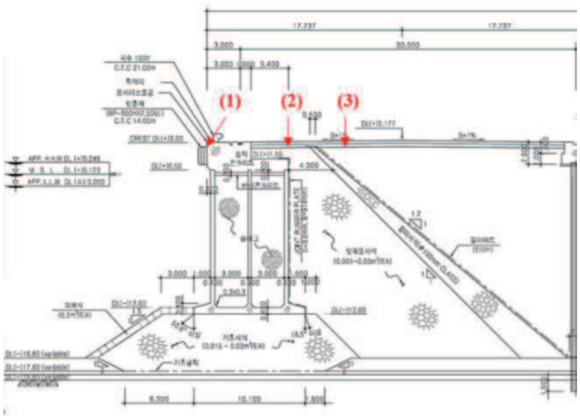

Fig. 1. Cross-section of caisson quay wall in Youngil Bay Port (MOF, 2018).

Table 1. Information of the damage to the quay wall at Youngil Bay Port during the Pohang earthquake of 2017 (MOF, 2018).

Location of damage	(1): The quay wall crown		(2): Backfill rubble	(3): Backfill soil
Type of damage	Tilting	Sliding	Settlement	Settlement
Degree of damage	Less than 1°	87 ~ 117 mm	110 ~ 220 mm	190 ~ 266 mm

3 EXPERIMENTAL PROCEDURE

The experiment was conducted at the KOCED Geo-Centrifuge Testing Center at KAIST using an earthquake simulator mounted on the centrifuge (Kim et al., 2013a, b). A rigid model box, which can be connected with the saturation system, was used for the dynamic centrifuge tests (Kim et al., 2022; Lee et al., 2022; Manandhar et al., 2021). The test was performed at centrifugal accelerations of 60 g. All results presented herein are in prototype units unless otherwise stated according to the centrifuge scaling laws (Garnier et al., 2007).

3.1 Model structures

The caisson gravity quay wall model used in the experiment was made of aluminum alloy (T6061). The dimensions of the model wall were determined by applying the centrifugal scaling law to the target prototype structure, and the required weight of the model wall was achieved by adjusting the thickness of aluminum (Lee, 2019a).

3.2 Test model preparation

The rubble and backfill soil were constructed by two types of dry silica sand with different mean diameters. The physical properties of the sands are presented in Table 2. The ground model was densified to a relative density of 85% by compaction for simulating the field ground conditions. The peak friction angles of the silica sands used in the simulation of the rubble and the backfill soil obtained through the triaxial test are 45.9 ° and 43 °, respectively. In addition, inter-friction angle between the rubble mound and the wall was 29° obtained through the direct shear test (Lee et al., 2017; Lee, 2019a). After the model preparation, the model was saturated with water. Since water was used in this test, the resulting permeabilities of the subsoil and backfill soil were 60 times greater than that required by the scaling laws for centrifuge modelling. Therefore, the excess pore pressure dissipates much faster than those for the prototype of the prepared soil model conditions (Lee et al., 2022). The saturation process is detailed in Manandhar et al. (2021).

Table 2. Physical properties of silica sands (Lee, 2019a).

Properties	Silica sand (Rubble mound)	Silica sand (Backfill)
USCS	SP	SP
D_{50}	2.10 mm	0.22 mm
C_C	0.35	1.11
C_U	2.40	1.96
G_S	2.65	2.65
PI	NP	NP
Max. unit weight:	15.30 kN/m^3	16.45 kN/m^3
Min. unit weight:	13.57 kN/m^3	12.44 kN/m^3

3.3 Instrumentation

The instrumentation layout is presented in Figure 2.

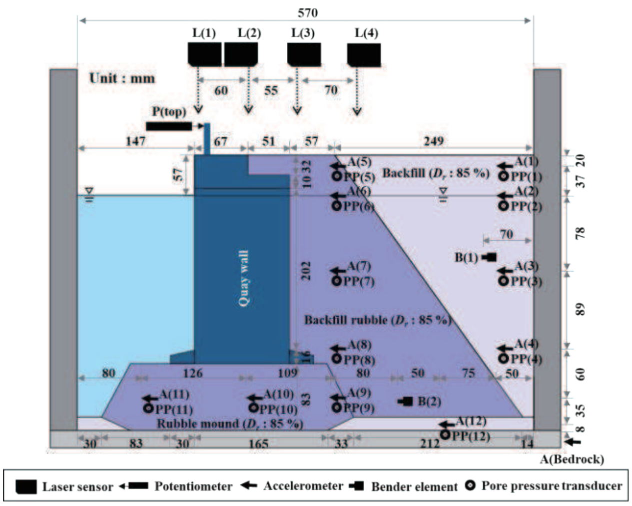

Fig. 2 Schematic illustration of test instrumentation (Lee, 2019a).

Twelve pairs of horizontal accelerometers and pore pressure transducer were buried in the soil to measure the time histories of acceleration and excess pore pressure at various locations of the soil. The residual horizontal displacements of the wall (D_h) were measured by potentiometer. Four laser sensors were used to measure the subsidence of the backfill and to check the bearing capacity failure of subsoil and the rotation angle of wall based on the settlement of the wall. Acceleration and D_h are positive in the active direction, and the settlement is positive in the downward direction from the backfill surface (Lee, 2019a).

3.4 Earthquake input motion

In this test, an earthquake record measured at bedrock of Pohang Port 5 km away from the Youngil Bay Port was used as the input earthquake motion. The earthquake record is shown in Figure 3. The input motion was imposed once with a similar acceleration amplitude (i.e. PGA of input motion : 0.35 g; PGA of measured motion of Pohang old port ; 0.33 g) at the bottom of the rigid box (Lee, 2019a).

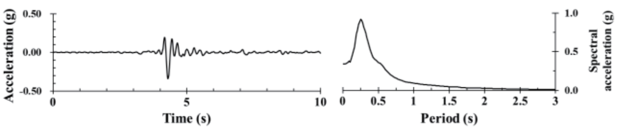

Fig. 3 Acceleration time history and response spectrum of input motion (Lee, 2019a).

4 CENTRIFUGE TEST RESULTS

4.1 Pore pressure and acceleration measurements

Figure 4 shows the pore pressure ratios (r_u) and the acceleration time histories at various depths in the soil model when Pohang earthquake with PGA equal to 0.35 g was applied to the bottom of the test model box. Also, the r_u values and the acceleration records measured at 3.4 m (Backfill rubble section) and 15.4 m (Backfill soil section) away from the model wall to the backfill soil direction at the same depth are shown in the respective figure simultaneously.

In this test, the responses of all the pore pressure sensors also included the generation of excess pore water pressure, generation of cycle components during the shaking, and dissipation process after the shaking. However, the dissipation process was rushed, since the water was used in this test (Lee, 2019a; Lee et al., 2022).

The r_u values of this test were less than 1 at all locations, and negative spikes did not occur. Therefore, it is judged that liquefaction did not occur in all locations of the soil model (Manandhar et al., 2021).

Furthermore, the comparison results of the r_u values between the backfill rubble and the backfill soil at each depth indicated that the excess pore pressure value of the backfill soil section is larger than that of the backfill rubble section. This phenomenon can be caused by that the permeability of the backfill soil is smaller than that of backfill rubble that the dissipation of excess pore water is relatively slow and the excess pore water is superimposed (Dakoulas & Gazetas, 2008).

Finally, the spikey behaviors, which are caused by the sudden transition between soft behavior when pore pressures are high and stiff behavior when the dilatancy triggers pulses of negative pore pressure (Kim et al., 2022; Lee et al., 2022; Manandhar et al., 2021), were not observed in the acceleration time histories at all locations.

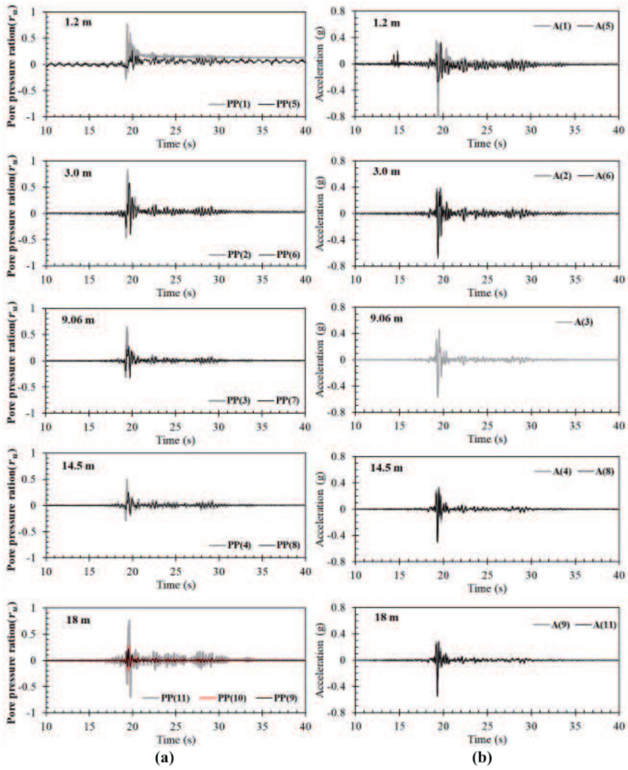

Fig. 4 Seismic responses of the test model: (a) Pore pressure ratio (r_u) of (PP1–PP10), and (b) Acceleration time histories of (A1–A10) (Lee, 2019a).

4.2 Displacement and settlement measurements

Figure 5 shows the time histories of horizontal displacement of the quay wall model and settlements of the quay wall model, backfill rubble and backfill soil.

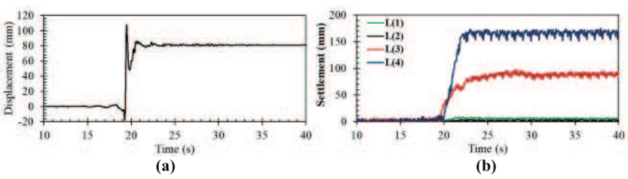

Fig. 5 Seismic responses of the test model: (a) Horizontal displacement time history of P(top), and (b) Settlement time histories of (L1-L4) (Lee, 2019a).

The permanent horizontal displacement and the degree of tilting of the quay wall model, and the permanent settlements of the backfill rubble and backfill soil were summarized in Table 3. Here, the permanent displacement and the settlements of the wall and backfill were obtained by subtracting the average value of the initial 500 samples from the mean of the last 500 samples of the displacement and settlement time histories, respectively. The degree of tilting of the quay wall model

© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5

was obtained by dividing the differences between the permanent settlements on the two sides to the distance between L(1) and L(2) (Lee et al., 2017).

Table 3. Damage information of the quay wall model (Lee, 2019a).

Location of damage	The quay wall crown				Backfill rubble	Backfill soil
Sensor		P(top)	L(1)	L(2)	L(3)	L(4)
Type of damage	Tilting	Sliding	Settlement			
Degree of damage	0.01°	80 mm	8 mm	2 mm	89 mm	166 mm

The comparison of the damage information of the quay wall model summarized in Table 3 and the actual damage information of Youngil Bay Port described in Table 1 showed that the quantitative values and the tendency of damage were similar, but the experimental results were slightly smaller than the actual damage records. The difference between the test result and actual phenomena seems to be due to the following reasons: (1) the earthquake record measured at Pohang old port 5 km away from the Youngil Bay Port was used as input motion and (2) the permeability of the soil model is bigger than the actual soil condition, since the test model was saturated using water (Lee, 2019a; Lee et al., 2022).

5 CONCLUSIONS

In this study, a centrifuge modelling for the damaged gravity-type quay wall in Youngil Bay Port during the Pohang earthquake in 2017 was performed. The reliability of the dynamic centrifuge test as a seismic performance verification method of the gravity-type quay wall was verified by confirming that the measured records of the model were similar to the actual records of the damaged wall. In addition, the test results can be used to validate the constitutive and liquefaction models for the numerical nonlinear effective stress analysis.

ACKNOWLEDGEMENTS

This research was part of a project titled "Development of performance-based seismic design technologies for advancement in design codes for port structures" funded by the Ministry of Oceans and Fisheries, Korea. This study was also supported by the Basic Research Project of Korea Institute of Geoscience and Mineral Resources (KIGAM).

REFERENCES

Dakoulas, P. and Gazetas, G. 2008. Insight into seismic earth and water pressures against caisson quay walls. *Geotechnique* 58(2): 95-111.

Garnier, J., Gaudin, C., Springman, S. M., Culligan, P. J., Goodings, D., Konig, D., Kutter, B., Phillips, R., Randolph, M. F., Thorel, L. 2007. Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling. *International Journal of Physical Modelling in Geotechnics* 7 (3): 01-23.

Kim, D. S., Kim, N. R., Choo, Y. W. and Cho, G. C. 2013a. A newly developed state-of-the-art geotechnical centrifuge in Korea. *KSCE journal of Civil Engineering* 17 (1): 77-84.

Kim, D. S., Lee, S. H., Choo, Y. W. and Perdriat, J. 2013b. Self-balanced earthquake simulator on centrifuge and dynamic performance verification. *KSCE Journal of Civil Engineering* 17 (4): 651-661.

Kim, Y. S., Lee, M. G., Cho, G. C. and Ko, K. W. 2022. Inertial behavior of gravity-type quay wall: A case study using dynamic centrifuge test. *Soil Dynamics and Earthquake Engineering* 155: 107196.

Lee, M. G., Ha, J. G., Jo, S. B., Park, H. J. and Kim, D. S. 2017. Assessment of horizontal seismic coefficient for gravity quay walls by centrifuge tests. *Géotechnique Letters* 7 (2): 211-217.

Lee, M. G. 2019a. *Study on seismic performance verification methods for performance-based design of gravity-type quay wall*. Dissertation, KAIST.

Lee, M. G., Ha, J. G., Manandhar, S., Park, H. J. and Kim, D. S. 2019b. Evaluation of performance-based seismic coefficient for gravity-type quay wall via centrifuge tests. *Soil Dynamics and Earthquake Engineering* 123: 292-303.

Lee, M. G., Ha, J. G., Cho, H. I., Sun, C. G. and Kim, D. S. 2021. Improved performance-based seismic coefficient for gravity-type quay walls based on centrifuge test results. *Acta Geotechnica* 16 (4): 1187-1204.

Lee, M. G., Sun, C. G., Cho, H. I., Kim, H. S. and Ha, J. G. 2022. Experimental study on seismic response of gravity-type quay wall considering input earthquake frequency and excess pore pressure buildup in backfill. *Ocean Engineering* 257: 111667.

Manandhar, S., Kim, S. N., Ha, J. G., Ko, K. W., Lee, M. G. and Kim, D. S. 2021. Liquefaction evaluation using frequency characteristics of acceleration records in KAIST centrifuge tests for LEAP. *Soil Dynamics and Earthquake Engineering* 140: 106332.

Ministry of Oceans and Fisheries (MOF), 2018. *Comprehensive report for Pohang Port earthquake damage investigation and restoration manual*. Seoul: Korea Port Engineering Corporation.