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Seismic behavior of an offshore structure based on geo-centrifuge test

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ABSTRACT: Seismic hazard induced severe earthquakes may give a critical damage on the offshore structures such as a wharf, a caisson, a quay wall, etc. In this study, a series of dynamic geo-centrifuge tests were performed to investigate the characteristics of the amplification of acceleration according to the frequency in a quay wall. Hachinohe wave which represents a long periodic wave and Ofunato wave which represents a short periodic wave are applied in tests. Consequently, more amplification occurred under applying Hachinohe wave condition even though the maximum acceleration values shows under Ofunato wave condition. Hachinohe wave also induced more lateral displacement than Ofunato wave, which indicates that the input frequency could lead to the amount of lateral displacement directly. Therefore, it is concluded that the appropriate consideration of the frequency characteristics shall be included in the assessment of seismic behavior of an offshore structure.

1 INTRODUCTION

Earthquake is one of the most complicated natural disasters and may induce various damages on civil structures. Offshore structures such as a wharf, a caisson, a quay wall, etc. are important to protect onshore facilities; therefore the dynamic stability should be obtained in designing stage. Offshore structures are exposed to oscillatory waves at all times, so hefty mass is normally required to ensure their stability. In this case, the seismic stability of an offshore structure should be carefully considered because the hefty mass induces excessive seismic inertia force on the structure. Therefore, the seismic behavior of an offshore structure should be understood to prevent its failure from earthquake loads. Harleman (1962) summarized theories on dynamic analysis of offshore structures based on analytical procedures. Laboratory tests are very useful means to clarify the seismic behavior of an offshore structure; so a number of studies have been performed on the seismic stability of offshore structures. Ghalandarzadeh et al. (1998) conducted shaking table tests on dynamic deformation of gravity quay walls and test results showed that the significant deformation of walls was a consequence of the combined effects of shaking and the development of pore water pressure in sand underlying the wall. Kim et al. (2005) proposed a new simplified dynamic analysis method to predict the seismic sliding displacement of quay walls based on the Newmark sliding block concept, and verified the proposed method by 1g shaking table tests. Hazarika et al. (2006) also executed a series of model shaking table test on a gravity type caisson quay wall protected by a cushion made from recycled product and the results show that the dynamic load against the caisson quay wall could be significantly reduced using the reinforcement. Zeng (1998) utilized a centrifuge modeling to investigate the seismic response of gravity quay walls and pore pressure. In the study, it was shown that cyclic shear stresses and excess pore pressures induced by base shaking can lead to deterioration of soil strength and stiffness, which reduces the fundamental frequencies of wall vibrations. Conti et al. (2013) conducted numerical modelling of centrifuge dynamic tests of circular tunnels in dry sand.

Based on the previous studies, laboratory tests using shaking table and centrifuge are applied to the characteristics of seismic response of offshore structures. In this research, geo-centrifuge test is employed to analyze the amplification of seismic acceleration in quay wall system according to the periodic variations of input earthquake waves.

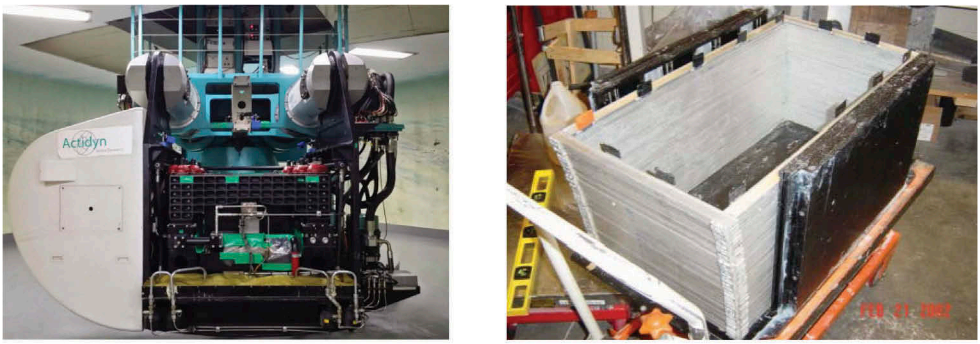
2 MODELING OF QUAY WALL SYSTEM

2.1 *Geo-centrifuge test*

Geo-centrifuge test was introduced in 1930s for the first time and a number of studies based on the test have been performed since 1960s. The use of geo-centrifuge modelling is particularly important for earthquake loading on civil engineering structures as it offers a unique opportunity to study the performance of structures before the earthquake actually happens (Madabhushi, 2015). Geo-centrifuge test can also complement the limitation and disadvantage of conventional laboratory tests such as shaking table test, cyclic triaxial test, etc. It can simulate the initial stress conditions in the ground, and investigate the long-term behavior of soil. Especially, the dynamic response of soil-structure system can be modeled precisely in dynamic geo-centrifuge test; therefore, it was utilized in the present study.

Physically reduced model test comparing with the prototype is very useful in civil engineering field because it is simple and economical. In the geotechnical regime, soil structures are always under the effect of in-situ stress, therefore the static and dynamic behaviors show different response to that of superstructures. Dynamic geo-centrifuge test was invented to simulate the in-situ stress condition in the ground by applying centrifugal acceleration to the model. It also may reduce the test cost dramatically without giving up the reliability for the test. Recent developments in robotics, control, electronics and miniaturization seem to be occurring so rapidly that any description of instrumentation or of techniques for modeling geotechnical processes at small scale must rapidly go out of date (D. M Wood, 2004). Figure 1 (a) displays the test apparatus.

In the geo-centrifuge test, the influence of the boundaries is important because the conflict and reflection of the input wave may generate inaccurate response of the specimen. In this apparatus, the Effective Shear Beam (EBS) is employed to minimize the influence of the boundaries of the container, as shown in Figure 1 (b). The EBS is composed of laminar boxes and the height of the each box is 63 mm. In the EBS, each frame is connected with roller bearings to avoid friction between boxes and rigidity of the boundaries; therefore, the whole container can play little part in the response of the soil system (Hushmand et al., 1988).



(a) Overview (b) EBS

Figure 1. Geo-centrifuge apparatus

Table 1. Properties of Jumunjin sand.

USCS	Gs	Max. dry density (kN/m^3)	Min. dry density (kN/m^3)	e_{max}/e_{min}
SP-SM	2.63	16.15	13.55	0.91/0.51

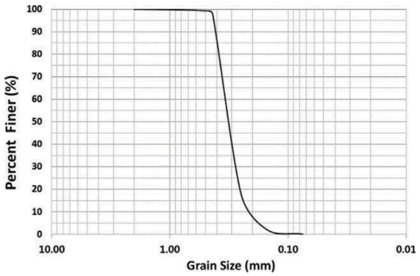


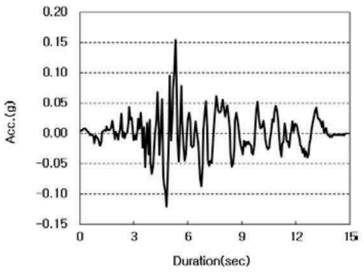
Figure 2. Grain size distribution curve of Jumunjin sand

2.2 *Test conditions*

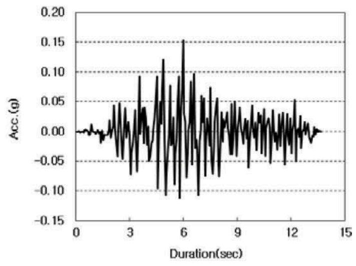
A caisson quay wall is modeled and seismic response accelerations at a few points are monitored. 2 cases of quay wall are considered according to the ground improvement methods. Jumunjin sand is utilized to comprise soil and Acrylic plate is used to simulate caisson. The dimension of the caisson is 340(length)mm × 312(width)mm × 360(height)mm. Physical properties and grain size distribution curves are displayed in Table 1 and Figure 2.

In case-1, ground under the caisson is improved by DCM (Deep Cement Mixing) method, and replaced by crushed stone in case-2. 2 kinds of Seismic waves are applied in tests such as Hachinohe wave which represent a long-term periodic wave and Ofunato wave which represent a short-term periodic wave. Figure 3 demonstrates the time history of each seismic wave. 50g of centrifugal acceleration is applied to the model. Response acceleration and displacement (lateral and vertical) are observed and obtained by accelerometers at 3 points and by LVDT at top of the model as shown in Figure 4. Figure 4 shows the model section of caisson quay wall and monitoring plan and Figure 5 displays the physical model which made of Polyacrylonitrile including its dimensions. Soil is modeled by compacted Kaolinite.

1-D seismic response analysis is performed to analysis the dynamic characteristics of each soil profile. Shake program is utilized and the amplification of acceleration is obtained. Soil profiles and analysis results are demonstrated in Figures 6 and 7, respectively.



(a)



(b)

Figure 3. Time history of each seismic wave. (a) Hachinohe (b) Ofunato

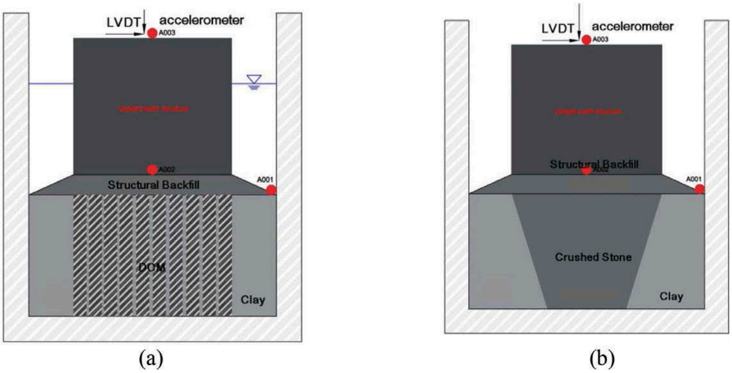


Figure 4. Schematic plan of quay wall modeling. (a) Case-1 (b) Case-2

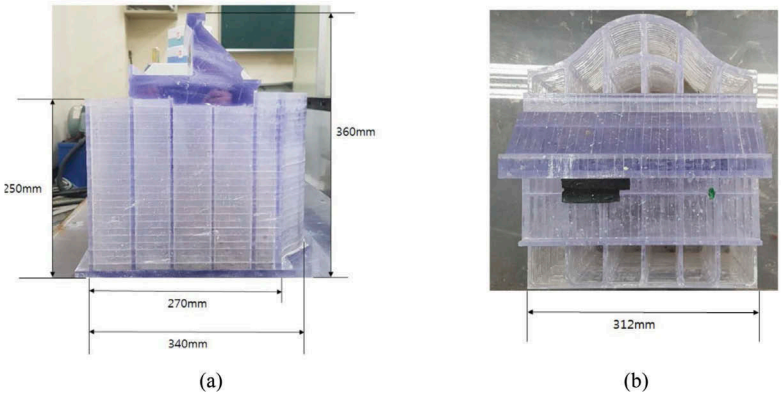


Figure 5. Physical model. (a) Section profile (b) Plan

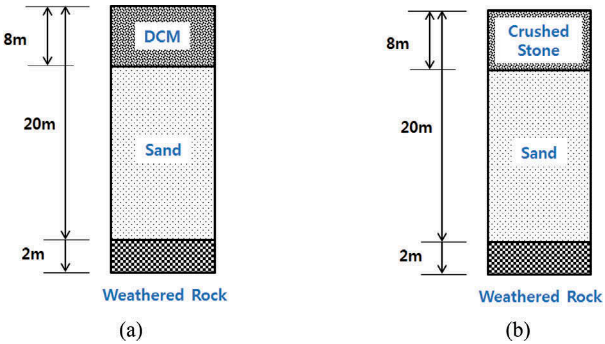
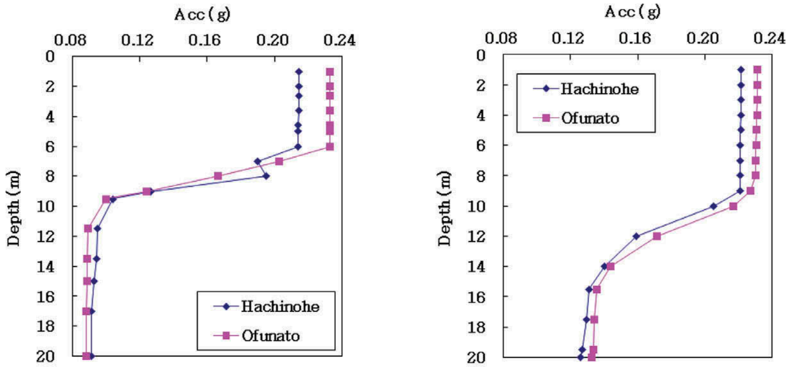


Figure 6. Soil profiles. (a) Case-1 (b) Case-2

Based on the response acceleration as shown in Figure 7, the response acceleration increases rapidly in depth around 10 meters, however, severe amplification of acceleration is not observed in DCM and crushed stone areas. This result represents DCM and crushed stone can play an effective role to restrain the amplification of response acceleration.



(a) (b)

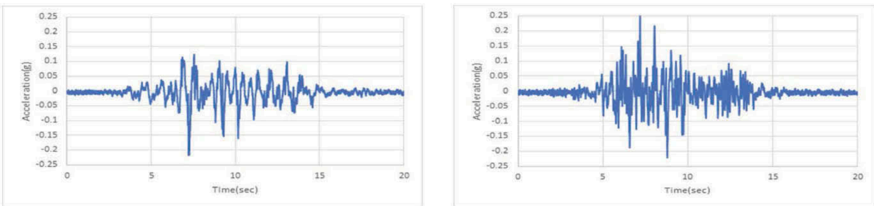
Figure 7. Sesmic response analysis results. (a) Case-1 (b) Case-2

3 TEST RESULTS

3.1 *Acceleration response*

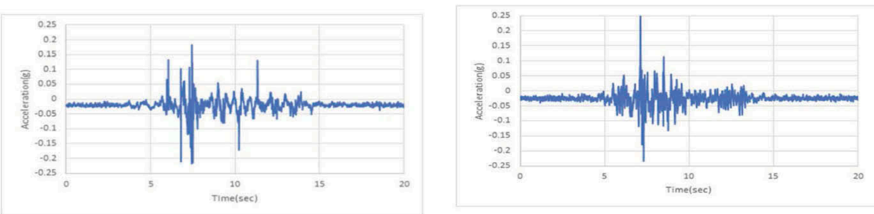
Time histories of response acceleration in case-1 are obtained as demonstrated in Figures 5 to 10, according to the input seismic waves. Peak acceleration values are shown in Table 1. Under Ofunato wave condition which represents short periodic characteristics, peak acceleration values shows larger than under Hachinohe wave. As shown in Figure 3, the accelerometer A003 is attached on top of the model, A002 is on top of structural backfill, and A001 is at the bottom of the structural backfill. In all cases, larger values of acceleration are found at A003 due to the amplification of acceleration. To clarify the degree of amplification of acceleration, the amplification ratio, Δ is calculated as Equation (1) below. Table 2 displays the ratio.

$$\Delta = \frac{A003_{\max} - A001_{\max}}{A001_{\max}} \times 100 \tag{1}$$



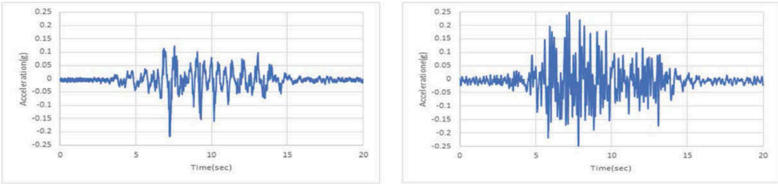
(a) (b)

Figure 5. Case-1: Acceleration time history at A001. (a) Hachinohe (b) Ofunato



(a) (b)

Figure 6. Case-1: Acceleration time history at A002. (a) Hachinohe (b) Ofunato



(a) (b)

Figure 7. Case-1: Acceleration time history at A003. (a) Hachinohe (b) Ofunato

Table 1. Peak acceleration values at each condition.

Location	Case-1 (g) Hachinohe	Ofunato	Case-2 (g) Hachinohe	Ofunato
A001	0.209	0.254	0.197	0.243
A002	0.210	0.239	0.191	0.239
A003	0.211	0.256	0.198	0.244

Table 2. Amplification ratio, Δ.

Seismic wave	Case-1	Case-2
Hachinohe	0.96	0.51
Ofunato	0.79	0.41

Table 3. Peak vertical and lateral (in a parenthesis) displacement at each condition.

	Case-1 (mm)		Case-2 (mm)	
Direction	Hachinohe	Ofunato	Hachinohe	Ofunato
Lateral	6.158	4.672	1.558	2.690
Vertical	0.204	0.242	0.121	0.210

where $A003_{max}$ = max. acceleration at A003; $A001_{max}$ = max. acceleration at A001.

For case-2 which reinforced by crushed stone below the caisson, the ratio increases about 24.4% under Hachinohe wave condition than Ofunato. For case-1 which reinforced by DCM method, the ratio increases about 21.5 % under Hachinohe wave condition than Ofunato. In all cases, the acceleration shows slightly decreasing trend at A002 and increases again at A003. To sum up, the amplification ratios show the larger values, around twice, under Hachinohe wave in all cases even though the maximum acceleration observed under Ofunato wave condition. Both the acceleration values and amplification are relatively small in Case-2, which indicates crushed stone replacement is more efficient solution to reduce seismic damage in this study. Addtionally, this quay wall system is more vulnerable to the long periodic seismic load due to the amplification of acceleration.

3.2 *Displacement response*

Based on the measurement result, the lateral and vertical displacements at the top of caisson (A003) are demonstrated in Table 3. Lateral displacement shows much larger values than vertical displacement in all cases. In case-1, the maximum lateral displacement occurred under Hachinohe wave condition. On the contrary, vertical displacement under Ofuato wave is larger than that of Hachinohe wave. In case-2, both the maximum lateral and vertical displacement occurred under Ofunato wave condition. Based on this result, it is deduced that crushed stone improvement can create more displacement under a short-periodic wave condition such as Ofunato wave. However, DCM improvement which shows more stiffness is more vulnerable to a long-periodic wave condition such as Hachinohe wave.

4 CONCLUSIONS

A series of dynamic geo-centrifuge tests were performed to investigate the characteristics of the amplification of acceleration according to the frequency in a quay wall. The quay wall system is divided into 2 cases based on the soil improvement method. DCM method is applied in case-1 and crushed stone replacement is applied in case-2. Hachinohe wave which represents a long periodic wave and Ofunato wave which represents a short periodic wave are applied in tests. As a result, the amplification of the seismic wave shows the larger values, around twice, under Hachinohe wave in all cases even though the maximum acceleration observed under Ofunato wave condition. However, the displacement is governed by soil improvement method. Based on the displacement measurement record, it is deduced that crushed stone improvement can create more displacement under a short-periodic wave condition such as Ofunato wave. However, DCM improvement which shows more stiffness is more vulnerable to a long-periodic wave condition such as Hachinohe wave. Therefore, it is concluded that the appropriate consideration of the frequency characteristics shall be included in the assessment of seismic behavior of an offshore structure such as caisson.

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