Seismic performance of gravity quay wall

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Abstract. Understanding the mechanism of the damages that occurs and the amount of displacement due to sliding in the gravity quay wall in ports during earthquakes are important factors because of the increase in the incidence of seismic disasters during recent decades. For this purpose, the investigation was performed using a shaking table test for two models of the quay wall in dry and saturated conditions. Cohesionless soil is used as a foundation for the quay wall and rubble soil used as a filter behind the quay wall and underneath. The dynamic performance of the quay wall is assessed in terms of both of the acceleration response and the seismic displacement. The results showed that the seismic wave amplification is increased significantly from the foundation of the gravity quay wall to the surface of the model, in which the highest amplification happened at the top of the quay wall model, thus, the design of this part of the gravity quay wall type caisson needs a great amount of the care and accurateness because the possibility of generating and propagating the cracks in this zone are very high.

Keywords: earthquake, gravity quay wall, shaking table test, liquefaction.

1. Introduction

Ports are considered important sites in the world because they play a role in national and international transport networks and have a significant role in the economies of countries. They supply transportation, distribution and other activities for the transportation of goods via water paths. In several countries, ports trade has been as the most preferred form compared to other types like air and land freight [1]. Quay walls are considered as one of the main parts of the ports. It has been used as the earth retaining construction for the docking of ships in harbors. Due to the high investment in port constructions, the seismic design and implementation of quay walls have become more significant day after day [2], therefore; they are considered as very important projects that which if subjected by any direct damage due to an earthquake, these would lead to restricting due to their role in the transportation to and from the harbors as well as their effects on the economy of the country. During recent decades, there have been many cases of damage that occurred in many ports in the gravity quay walls induced by the seismic liquefaction [3]. In 1993 at Kushiro-Oki and in 1994 at Hokkaido Toho-Oki, the liquefaction occurrence in both the saturated foundation and the backfills was classified to be one of the major damages of gravity quay walls due the earthquakes [4]. In addition, in Kobe, Japan, in the 1995 Hyogo-ken Nanbu earthquakes, the liquefaction failure caused the major damage to port infrastructure as shown in figure 1. The typical kinds of failure recorded after the Kobe earthquake were: seaward movement, maximum 5 m, and average 3 m whereas the walls settled nearly by 1 to 2 m and inclined about 4 degrees [5]. Furthermore, reports of 24 marine constructions in 1999 at Kocaeli-earthquake in Turkey, illustrated that the backfill of quay walls also liquefied which resulted seaward displacements of the quay walls [6]. The same damages have been observed in the 1999 Chi-Chi earthquake in Taiwan [7].
For better understand the seismic behavior of this structure, many of the researchers carried out studies by using numerical and experimental modeling studies. In the field of experimental work, a new simplistic method by Newmark sliding block analogy to estimate quay wall displacement using a series of 1-g shaking table tests was proposed [8]. Some researchers used physical modeling to study the seismic mitigation of gravity quay walls. The effectiveness of sand compaction piles as a technique of damage mitigation behind the wall, using a series of 1-g tests were investigated [9]. A series of 1-g shaking table model tests, the efficiency of the sheet pile walls was tested as a method prevention of damage in the waterside of caisson quay wall [10, 11]. They verified the typical site of these sheet pile walls were in the waterside of the caisson quay wall. In the field of numerical modeling, assessment the dynamic response of the quay wall in the Kobe port is done and investigating the soil-structure interaction system has been proposed [12]. Evaluation and investigation how the soil density improvement effect on the reduction damage in the quay wall on the basis of the numerical modeling and experimental testing have ben inspected [13] (shaking table test). Seismic vulnerability curves for two kinds of block quay walls with various geometrical clearly indicates that the developed vulnerability curves are greatly based on existing geometric and geotechnical situations [14]. The modified pseudo-dynamic method which solves barriers for assessing the seawall stability in passive situations under the combined effect of the tsunami is formulated.

In this paper, the seismic behavior of the gravity quay wall will be studied using experimental modeling. In the experimental work, two type of models in the laboratory have been tested (dry model and saturated model/ filled with water) in the laboratories of University of Wasit, Engineering faculty, to inspect the effect of liquefaction phenomena on behavior of quay wall model.

2. Experimental Modelling
2.1 Design of the Model and zone definition
In this study, a laboratory physical model was performed and the gravity quay wall (type caisson) was modeled, as shown in the figure 2 and table 1, which simulate the caisson quay wall in reality. The scale down of the caisson quay wall model is 1/50 of the typical prototype in the port island and Rokko islands of Kobe, Japan [11]. A concrete model was used as a model for the caisson type gravity quay wall. The model seated on a gravel layer called the rubble mound. The gravel filter zone behind the quay wall is called rubble filter. The soil under the rubble mound represents the foundation. The soil that located behind the rubble filter is called backfill. The zone below the backfill and seawater is representing the marine clay. Fine sand with different relative densities was used. The fine sand was used to represent the layer of marine clay at the quay wall location (in reality). The fine sand with relative density (Dr = 55%) is used, to avoid the challenges and time required for the collection of non-liquefiable clay in the preparation of the sub-layers.

Figure 1. Typical damage of quay wall in the port of Kobe, Japan during 1995 Hyogoken-Nambu Earthquake [8].
Table 1. Dimensions details of quay wall model showed in figure 2.

| Variables | Dimensions (cm) | Details |
|-----------|----------------|---------|
| B         | 20             | Dimensions of quay wall Body |
| H         | 30             | |
| BF        | 24             | Dimensions of filter layer with slope 1:1.2 |
| HF        | 25             | |
| Br        | 55             | Dimensions of rubble mound layer |
| Hr        | 5              | |
| BT        | 190            | Dimension of container |
| HT        | 85             | |
| Hw        | 30             | depth of water |
| H1        | 30             | Thickness of foundation soil layer |
| WR        | 85             | |
| WB        | 85             | Width of back fill layer behind the quay wall |

2.2 Material properties
The soil used for the quay wall foundation model and backfill is sand of golden yellow appearance. The sand properties that used in this study are very similar to the characteristics of the HST95 silica sand, and this type of sand was used by many research studies in several experimental work around the world [15, 16]. Firstly, for 24 hours, the sand was placed in a laboratory oven to be dried. Then, to get rid of the large particles, the sand has been sifted using sieve No. 10. Figure 3 showed the distribution of size particle, PSD for the sand that was prepared. From the comparison with the properties of HST95 silica, HST50 silica sand and Ottawa sand, sand particle size that used in this study has properties close to the traditional silica sand that has been widely used in many research centers and in geotechnical physical modeling. [17]. Table 2 demonstrates the main physical properties of the sand used beside each property of both HST95, HST50 silica sand, and Ottawa sand. The purpose of using this sand is to be compatible with what others around the world use in physical modeling. On the other hand, for dispersion of the dead load of the caisson and increasing foundation bearing capacity, the caisson was rested on rubble with minimum mean particle size (i.e. D50) around 3mm and maximum D50 around 9mm and dry unit weight(14 kN/m³). For decreasing the active earth pressure effecting on the caisson quay wall, the gravelly material in the backfill was used because of its large internal friction with the same properties of rubble layer [19, 20].
2.3. Input motion

A 1-g shaking table test has been conducted for two models of the gravity quay wall type caisson which includes cohesionless soil (i.e. Sand) in the foundation and backfill. Testing the seismic behavior of this system is the main objective of this paper and this can only be done by fabricating a model that can be used as reference model for comparison with other tests, thus; dry model will be the reference model. The shaking table machine can generate just a sinusoidal wave (i.e. single predominant frequency) because it has been designed in a simple way in order to reduce the manufacturing cost. To accredit the input motion of the two shaking table tests, an accelerometer was set at the container base as an input motion for the model. Figure 4 showed the input motion used in this paper. Despite the concept of the manufactured shaking table that applies the sine wave form only, it was clearly seen that there are other frequencies manifested during the shaking depending on the measured data of the acceleration from the accelerometer fixed at the container base. In fact, these recorded frequencies are very important for good representing of the actual earthquake, which generally have tens of frequencies.

2.4. Experimental Tests
During this study, the dynamic response of gravity quay wall type caisson was studied in the experimental work in two cases, firstly in the case of dry model and secondly in the case of saturated model ground /filled with water.

2.4.1. Shaking Table Test of Quay Wall in Dry Case (T-1). The quay wall model was tested using cohesionless soil in dry conditions. For model preparation in a medium relative density condition (RD=55%), the pluviator technique (air sand) was used by using a mechanical pluviator that was previously designed and manufactured [21, 22]. Quay wall model details in the dry state consist of (sand foundation layer, rubble mound, quay wall model, filter zone and sand backfill layer). Before starting of preparing the sandy layer foundation of the model, an accelerometer sensor is installed horizontally (Acc1) in the direction of motion at the base of the shaking table (uniaxial accelerometer) to measure the input motion. When the base layer height reaches 30 cm, another sensor is placed (Acc2) at a distance 15 cm underneath the quay wall body. Once the height of the base layer is completed to a required thickness (40 cm), layer of rubble mound is prepare from gravel having properties mention in the section 2.2 ,this particle is set in a mold with plate thickness 2 mm to take the required shape of layer. After that, the quay wall model is placed on it, and fixed well (no contact with the side wall of the container. The quay wall model is equilibrated using an alcohol scale when it is placed on the rubble mound. Then, the third accelerometer was installed on the quay wall surface to measure the amplification in acceleration on the crest of quay wall model. In addition, filter zone is placed in the container, which had the same gravel material used in the rubble mound. Layer of geotextile is placed on the filter zone layer to prevent the sand grains particles to cross from the backfill area of the filter zone. The last step is to fill the backfill area with the sand used in the base layer with a medium density (Dr =55%) by using the mechanical pluviator [22]. On the other hand, two sensors of linear variable differential transducers (LVDTs) were used, the first was placed on crest of the gravity quay wall model to measure the settlement which occurs for the model during the shaking, and the second is placed horizontally on the model from the top and its purpose is to record the seismic horizontal displacement during shaking. Wooden bars fixed in a parallel direction to the width of the container (fixed parallel to the larger dimension in the gravity quay wall model), to prevent any unwanted movement during shaking. All wires of these sensors were come out from these halls to the data logger. Figure 5a represents the shape of quay wall model in dry case.

2.4.2. Shaking Table Test of Quay Wall in saturated Case /filled with water (T-2). In this test. The gravity quay wall model was constructed on the same of soil layers for the previous test and the processing of saturation was taking around 72 hours. The left side of the gravity quay wall was filled with water by using a pump with slow discharge velocity to prevent the effects of any stress on the soil that may occur. During the process of filling with water, the quay wall model that was taken approximately one hour, and to prevent any seepage in the direction of the backfill soil from the layer of rubble mound, a layer of water stop material is used at the waterside of the model. Figure 5b shows the quay wall model before the test.

![Figure 5a](image1.png)

![Figure 5b](image2.png)

**Figure 5.** Quay wall model type caisson in saturated cased /filled with water.

2.5 Results and Discussion of Experimental Tests
2.5.1. Dynamic Response in Dry Case (T-1)
2.5.1.1. Acceleration Response. Through the data recorded by the accelerometers installed in different places of the model, the acceleration response of the caisson quay wall model was evaluated; where the response is assessed through the soil layers (sand) as well as the gravity quay wall model itself. The data recorded in the accelerometers through the test are shown in figure 6. It clearly shows in the from the acceleration data recorded in Acc2 and Acc3 that the base movement (i.e. Acc.1) has been getting a high amplification (i.e. the motion gets amplification from the base of the foundation to the ground surface), also the great response to the gravity quay wall. An important fact is that tall buildings (the length of the wall of the gravity quay wall here) are more responsive to small frequencies, so the periodic free vibration of the wall of the gravity quay wall is not surprising. From figure 6, it is possible to observe the mechanism of how the quay wall model behaves under the influence of the dynamic motion. From the data recorded by the first accelerometer, it can be concluded that the value of the peak acceleration value of the input motion is 0.8g. The response for the foundation of gravity quay wall model (Acc.2) was about 1.12 and this value gave an amplification factor about 1.4 (The amplification defined as the ratio of the magnitude of the acceleration measured at any depth to the acceleration of the input motion.). The nature of the amplification by the acceleration that took place corresponds to the fact of the movement from the base of the foundation to the surface of the model, which was previously seen by [11]. On the other hand, significant acceleration was recorded at the crest of the model compared to the motion at the base of the model and this means that consideration must be given to the need to take care of this part of the structure when designing in seismic areas.

![Figure 6. Time history of acceleration of the gravity quay wall system (T-1).](image)

2.5.1.2 Dynamic displacement of the Gravity Quay Wall Model
The dynamic horizontal displacement and settlement for the gravity quay wall were measured using the LVDTs installed on the top of the gravity quay wall model. The amount of settlement (red line) of the gravity quay wall model is greatly affected by the increase in shaking intensity (i.e. from t = 0.92 s to t = 5.86 s) as demonstrate in figure 7. The highly vertical displacement (settlement) that can be measured with LVDT is 50 mm; the gravity quay wall model starts to settle after 0.92 seconds, (see the input motion at this time). From the shaking test, it could be noticed that the effective shaking time is 4.94 seconds. During this time, the gravity quay wall model sunk into the soil. Moreover, the gravity quay wall model has been overturned after 5.86 sec and later on (see figure 7).
For the horizontal displacement, it is also measured "by another LVDT, which is fixed horizontally at the crest of gravity quay wall model. It is fixed on the waterside, for comparing the value of the cyclic horizontal displacement of the model when it is empty of Water and when it is filled with water. From the figure 7, it is clear that the settlement form is similar to the shape of the horizontal displacement, and the same sensor type used (50 mm) the positive cyclic displacement to represent the gravity quay wall model movement in the direction of the backfill and the negative movement in the direction of the waterside. The largest amount of horizontal displacement was captured at time (t =1.03s). The amount of horizontal displacement may have disappeared after (t = 1.21s) from starting the movement, and this can be attributed to the overturning failure (at the heel point of the gravity quay wall model). After that, only negative horizontal displacement is appeared until the model reaches failure (this can be seen by following figure 7 by noticing the amount of displacement and time).

2.5.2. Dynamic Response of the Gravity Quay Wall in saturated Case/filled with water

2.5.2.1 Acceleration Response. The acceleration data measured by accelerometers fixed in the different locations of the model are shown in figure 8. From the acceleration data, it can be seen that the acceleration recorded by Acc2 has diminished about the data recorded by Acc1, and this is due to a rise in the pore water pressure in the substrate layers of the soil and thus, the occurrence of the phenomenon of liquefaction. As well as the effect of the model's weight of gravity wall in which damps the soil movement under the model. The acceleration measured by Acc. 3 (located at the crest of the quay wall model) demonstrates the hysteretic acceleration response for the model. This, in reality, occurring due to the cyclic wave pressure at the face of the gravity quay wall in the waterside (i.e. the quay wall model motion at the direction of waterside).
2.5.3. *Dynamic displacement of the Gravity Quay Wall Model.* Both the settlement and dynamic horizontal displacement that recorded at the gravity quay wall model in test 2 (filled with water) was very different from the previous case as illustrates in figure 9. The recorded positive and negative displacements refer to the motion of the quay wall model in the direction of the backfill and waterside (due to kinematic energy of the water at waterside and backfill soil in the backward of the model). In this test, the cyclic motion of the model begins at a time of 1.03 sec and the model is moving in the positive and negative directions. The movement in the negative direction disappeared at a time of 1.63 sec, and then the model begins to move in the positive direction only. Since the displacement sensor is fixed to the waterside, the maximum positive displacement was recorded by the horizontal LVDT at a time of 6.33 seconds.

![Figure 9. Horizontal cyclic displacement and settlement of quay wall model (T-2).](image)

The measured settlement for the quay wall model does not differ from the measured values from the other tests. 8mm is the measured settlement after 6.53 sec and it was impossible to measure the settlement after this time due to limits of the LVDT. The measured settlement seems to be more than the measured value from both the empty dry and saturated models. This can be attributed to the fact that occurred shear deformation for the rubble mound layer beneath the gravity quay wall model during the shaking due to heavy weight and liquefaction of the foundation sand.

3. Conclusions

The present paper deals with experimental (shaking table test) to investigate the dynamic performance of gravity quay wall. This was carried out by performing two laboratory model tests in two cases (dry case, saturated case/ filled with water). The major conclusions are summarized below:

1- The results showed that the seismic wave amplification is increased significantly from the foundation of the gravity quay wall to the surface of the model. In which the highest amplification happened at the top of the quay wall model, so, the design of this part of the gravity quay wall type caisson needs a great amount of the caring and accurateness because of the possibility of generating and propagating the cracks are very high.

2- The liquefaction occurrence (caused by the rapid rise in pore water pressure due to cyclic loading) is produced when the gravity quay wall is based on medium saturated soil, which leads to failure underneath the quay wall model. This has happened in case of model filled with water

3- The vibrations and the acceleration response in the case of the full water in the waterside are greater than the vibration or the response in the case of an empty reservoir. This occurred because the water
moves back and forth during the vibration, which governed a great hydrodynamic pressure at the waterside of the quay wall model. However, at a certain time, this made to increase acceleration and in other side reduces the acceleration. In addition, when the applied frequencies (frequencies of the input motion) correspond to the natural frequency of the system, amplification occurs in the acceleration.

4- The static shear stress in foundation due to backfill earth pressure of quay wall act as shear load in foundation, which would be further increased by relative inertia force during dynamic load of the gravity type quay wall. This shear load in foundation is mainly responsible for shear deformation at foundation toe of the quay wall during shaking.

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