Quick Review of Seismic Behavior of Gravity Quay Wall

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Abstract. Earthquakes are one of the worst natural disasters that effect directly both human life and infrastructures around the world. The seismic behavior of a gravity quay wall has been outlined from art-of-literature in this review paper. Based on previous studies available on the subject, the paper includes a simplified introduction of gravity quay walls structures followed by the loads acting on the quay wall which are used in the design, modes of failure, forces generated during earthquakes, method of evaluation of displacement of gravity quay wall and the techniques that used to reduce the damage caused by liquefaction during earthquakes. Through the discussion, it was concluded that when shaking amplitude is high at low frequency and the soil of the foundation underneath the quay wall is loose, an increases in the distortion of the wall is noticed. Pore water pressure increasing in the soil and backfill soil leads to an increase in the amount of deformation twice the case of constant pore water pressure. The sliding of the caisson is greatly increased when liquefaction occurs in the backfill soil and the different used techniques to reduce the liquefaction damage during the earthquake had good results in several locations.

Keywords: Quay wall, Earthquake, Seismic Displacement, Liquefaction, Deformation.

1. Introduction
Quay walls infrastructure can be classified as a land-retaining structures at which the ships can dock. Anchors are usually equipped with ropes for the purpose of unloading and loading goods to and from goods ships. The quay wall is used in the cargo loading and unloading process, which is usually done by crane or heavy equipment that moves along “alongside ships”. The quay walls advantages are easy construction technology, good reliability and favored cost [1]. The 1995Hyogoken-Nambu earthquake-induced significant damage to the gravity quay walls which surrounded many recent artificial islands in the port of Kobe and the area of Osaka Bay. Because the walls have moved a few meters towards the sea, the ports have stopped operating (out of services) for a long period of time. Despite this great effect of the distortion of walls, its causative mechanism was not easily clearly known after the earthquake. Figure 1 demonstrates the quay wall cross section that used in a port of island [2].

An old constructed sea floor, made up on soft clay, was removed and replaced with sand for the purpose of supporting the heavy weight of the quay wall. This sand is known as foundation sand. In the Kobe port area, the quay wall is built of large caisson boxes with sand. Figure 2 demonstrates the typical distortion of Port Island's caisson wall at Kobe harbor. The wall was tilted towards the sea, and a lot of cracks formed on the surface of the backfill [3].
Figure 1. Caisson type gravity quay wall, cross section [2].

Figure 2. Earthquake induced deformation of gravity quay wall in port Island [3].

Similar kinds of damage have been recorded from a lot of past earthquakes; such as Port of San Antonio, Chile, in 1985 [4]. Many studies at different research centers around the world have been conducted on caisson quay walls to investigate the dynamic response and the seismic performance. A centrifugal test by using a dry sandy backfill is carried out [5]. Development of slip plane or localization of shear strain has been illustrated. Shaking table tests is conducted by [6] and the results revealed that localization of strain occurs and the earth pressure rapidly decreases to a level of active pressure upon the start of the wall sliding. A centrifugal experiment on a gravity quay wall has been prepared and tested [7]. A centrifugal model’s small scale gravity quay wall showed that the lateral wall movement stopped at the end of the shaking, possibly since the subsoil had 60% relative density, which was not very loose. 1-g shaking table experiments are performed by [8] and it was illustrated that the pore water pressure didn't develop greatly below the gravity quay wall while the liquefaction occurred in the backfill soils. Shaking table experiment tests on a model of caisson quay wall are conducted by [9]. They demonstrated that the earth pressure acting on the caisson was in phase with the seismic inertia force when the backfill soil liquefied. Effects resulting from the increase in pore water pressure in the backfill and foundation soils on the dynamic response of gravity quay wall using the shaking table models have been investigated by [10]. They observed that the seismic deformation of quay walls are strongly influenced by the excess pore water pressures of backfill soil and foundation strata (the inspected deformation was twice in case of pore pressure generation comparing in case of no pore pressure). The reducing of the tilt of the quay wall towards the sea, slipping and the settlement of a caisson quay walls during the earthquakes by using deformable panels has been studied by [11]. The results showed that the deformed panels had significantly reduced the amount of movement toward the sea as well as the settlement and the inclination of the wall. The mechanism of the deformation occurrence in the gravity quay walls type caisson by using the in situ soil freezing sampling in a shaking table test was inspected carefully [12]. The results showed that the deformation of the caisson wall increases dramatically with the increase in the pore water pressure in the backfill and the foundation soils of the wall.
This review paper focuses on the seismic behavior of the quay walls (gravity type) and the failure mechanism form and how the design loads, earthquake loads and subsoil strata properties effect the dynamic response of such structure. This will be done based on previous researches that were previously reviewed in this field.

2. Failure modes of gravity quay wall
The forms of failure were seen in many previous studies, as well as in the sites of ports and man-made islands after the earthquakes were slipping, reversal, deep slipping, and failure of the foundation. So, the stability calculations of the quay wall structure revolve around several important things, which are settlement, carrying capacity of the foundation, slipping and overturning [13]. The port quay walls are designed at a certain seismic motion boundary. Therefore, when the seismic movement exceeds the permissible design limits, the caisson port wall moves toward the sea, and that is the failure by settlement in the backfill behind the wall. Such failure mode was noticed during the 1995 Hyogoken-Nambu strong earthquake with a 0.54 g destructive peak ground acceleration, and this limit exceeds the design limit for the cassion-type quay wall’s site where it was designed with seismic parameters of 0.1, 0.15. Figures 3 and 4 show the details of the cross sections of these walls that were designed according to seismic coefficients of 0.1 and 0.15.

Figure 3. Port Island quay wall; cross sectional view [12].

Figure 4. Schematic view of the quay wall deformation at Port Island [12].
The caisson quay wall shown in figure 5 has moved towards the sea with a distance of 3m, and settled approximately 1 m and it has a slope with an angle of 3 degrees. The caisson quay wall shown in figure 6 has moved towards the sea with a distance of 4 to 5 m, and settled approximately 2 m and it has a slope with an angle of 4 to 5 degrees. During the earthquake mentioned above, there was no collapse or overturning of the walls, whether in the port of Kobe or other ports [12]. Also, the quay wall damages are occurred in many of past seismic events such as damage of quay wall observed in Niigata Earthquake in 1964. The damage’s characteristic of gravity quay walls were the irreversible movement, rotational failure, and the differential settlement of the quay walls and significant ground deformation in the backfill (Earthquake Resistance Design Code in Japan, 2000).

![Figure 5. A quay wall cross sectional vie at Rokko Island [12].](image)

![Figure 6. Deformation of Rokko Island quay wall [12].](image)

In Japan, Kyushu earthquake, 2005, few centimeters towards the sea were occurred to the quay walls in Fukuoka port and few centimeters subsidence as well as shown in figure 7 [3].
3. Forces components governing during earthquake on gravity type quay walls

The components of the forces affecting the quay walls and the phase relationship between the components of these forces must be correctly estimated during the dynamic analysis and the stability of the quay walls. In general, forces compounds consist of the inertia force of a wall, the lateral force of the soil (foundation) underneath and behind and the hydrostatic force of water. For each force component, the magnitude of each component and the phase relationship for each force is changing with time and greatly affected in the event of an increase of the pore water pressure of the backfill soil behind the quay wall as shown in figure 8.

The forces present before the earthquake is occurring are limited (i.e. the force of the soil or foundation underneath and behind as well as the force of the water). During an earthquake, additional forces are governed along the quay wall, which are the wall’s inertia force, the dynamic response of soil force and the dynamic water’s force. Each of earth’s dynamic forces and dynamic water forces is divided into two components, the fluctuating component, and the non-fluctuating component.

Therefore, the total forces acting along the quay wall are the static soil force (i.e. at rest condition due to lateral earth pressure), the static water force, the inertia force of the quay wall structure, the fluctuating and non-fluctuating components of the soil dynamic force as well as the combination of the fluctuating and non-fluctuating seismic water force as shown in figure 9 [14].
4. Quay wall seismic displacement evaluation

There are many simplified dynamic procedures and methods that have been proposed and validated numerically and experimentally to estimate the sliding seismic displacement of the quay wall according to considerations of variance in the wall thrust, which is greatly affected by any increase in the pore water pressure generated in the backfill behind the wall during the earthquake. There is a method used for this purpose in which the concept of the Newmark’s sliding block and variation of yields acceleration of the block are considered. This method is basically considered the change of the quay stability according to the wall’s thrust to estimate the seismic displacement.

The Newmark sliding block approach can be defined as the soil-structure block yield acceleration as the magnitude of the block acceleration when the sliding safety factor is 1.0. The evaluation of seismic displacement in this method can be estimated mathematically by using principles of the mathematical integration (i.e. twice) of the differences amount between the ground acceleration and the yield acceleration. Various methods have been suggested for calculating the block displacement by acceleration integration, among them, the method of [14-17] is widely used. Figure 10a illustrates the time history of the ground acceleration and compares it with the yield acceleration, ay. The displacement of the wall begins at the point x and at which the amount of the acceleration of the soil block has a value greater than ay (i.e. figure 10c). The accumulated seismic displacement of the block is found by twice integration of the difference between the ground accelerations and the yield acceleration until the seismic velocity value reaches zero as shown in figure 10b [14-15]. This procedure are followed by many researcher around the world in the computation of the seismic displacement of gravity dam [18]; and the seismic performance of piled-reinforced slopes [19].

Several studies have been conducted to estimate the displacement of the sidewalk wall during earthquakes. The displacement mechanism of the gravity quay wall by using shaking table test is investigated by [14]. They concluded that the quay wall lateral displacement has been stopped at the end of shaking irrespective of the caisson box weight and sand density.
5. Concept of Liquefaction Induced Quay Wall Damage Mitigation

There are many studies on seismic liquefaction in terms of causes, mechanism, and consequences. Regardless of the causes of liquefaction, the measures taken to relieve liquefaction should be able to prevent the development of unacceptable amounts of deformation resulting from. Therefore, it is possible to prevent a large deformation in the soil through the following measures (JGS, 1998):

(i) Preventing the generation of pore pressure increase, this is done by condensing the soil by replacing it with soils that are more stable (soil improvement by soil replacement) and reducing the degree of saturation as well as chemical grouting.

(ii) By installation of gravel drains. For immediate dissipation of excess pore pressure.

(iii) Restraint of remaining strain; for instance, the embedded quay or retaining walls or any mechanical reinforcement together with equilibrium between gravity force and the buoyancy reaction to avoid sudden settlement and floating.

Finally, there are other many techniques used to reduce liquefaction, for example chemical grouting, densification, embedded sheet pile walls, and Sand Compaction Piles (SCP).

6. Conclusions

This paper was directed to focus on the dynamic response of gravity quay wall based on the experimental data of a literature studies. According to the limits of the mentioned parameters in this study, the conclusions that can be obtained demonstrate the effectiveness of the earthquakes on such infrastructure and how the earthquake amplitude is significant and when the frequency is in the destructive range (i.e. below 3 Hz) and the backfill soil behind the quay wall and the soil underneath is in the loose state, this leads to increases in the distortion of the wall. The effect of excess pore water pressure in the backfill soil and foundation layers increase the seismic deformation about twice compared with constant excess pore water pressure case. The slipping of the caisson is greatly increased when liquefaction occurs in the soil of the backfill.
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