International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

2010 - Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

26 May 2010, 4:45 pm - 6:45 pm

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Recommended Citation

Khodabakhshi, Masoomeh and Baziar, Mohammad Hassan, "Evaluation of Deformation Behavior of Quay Walls Under Earthquake Loading" (2010). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 21.
https://scholarsmine.mst.edu/icrageesd/05icrageesd/session05/21

Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

EVALUATION OF DEFORMATION BEHAVIOR OF QUAY WALLS UNDER EARTHQUAKE LOADING

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ABSTRACT

Ports are often regional economic centers and important components of regional and local transportation lifeline systems. Because of these reasons, the downtime of the ports due to natural disaster such as an earthquake results in severe economic loss. Gravity quay walls are the most common type of construction for docks because of their durability, ease of construction and capacity to reach deep seabed levels. Past earthquakes demonstrated that the seismic behavior of port structures such as quay walls was significantly governed by the properties of soils. The 1995 Hyogoken- Nanbu (Kobe) Earthquake brought great damage to structures in the Port of Kobe, which is one of the primary ports in Japan. In the present work, caisson type quay wall, damaged by 1995 Hyogoken- Nanbu earthquake, is first numerically analyzed and then seismic behavior of quay wall is investigated. The results are also compared with the observed data consisting seaward displacement, tilting and settlement. The results of the numerical analyze shows good agreement between the numerical simulations and observed data.

Keywords: Earthquake; Liquefaction; Quay wall

INTRODUCTION

In many of the recent earthquakes, Port structures such as gravity type quay walls, vertically composite walls, cantilever retaining walls and etc have suffered significant damage.

The occurrence of earthquake in the regions with saturated loose sand is caused the increase of the pore water pressure and the decrease of shear strength that may result in liquefaction. A soil deposit that was liquefied, behaved like fluid.

The liquefaction phenomena in the loose, saturated sand beneath gravity quay wall contribute to the damage of the ports. These structures built for protecting the backfill in front of cracking and anchoring the ships. It was found that the occurrence of the liquefaction in back fill was the main reason for the damage from many recent earthquakes to gravity quay walls such the 1964 at Nigata Port (Hayashi, et al., 1966) , the 1993 at Kushiro- oki and the 1994 at Hokkaido Toho- oki (Sasajima, et al., 2003) .

The importance and sensitive role of quay wall and weak performance of these structures during the liquefaction of soil caused the progress of researchers in this part to founding the behavior of quay wall during the earthquake.

Parameters Characterizing Gravity Quay Wall

In order to enhance the applicability of the simplified dynamic analysis for gravity quay walls for general geotechnical conditions, seismic performance of gravity quay walls was studied through effective stress analysis by varying structural and geotechnical parameters of a quay walls under various levels of shaking.(Iai et al., 1999) . Major parameters studied are width to height ratio of a gravity walls,W / H , thickness of soil deposit below the wall, $D1$, and geotechnical conditions represented by SPT N- values of subsoil below and behind the wall that are showed in Fig.1.

The most sensitive parameter were the SPT N- value of subsoil below and behind the wall, the thickness of the soil deposit below the wall and width to height ratio of a gravity walls. The results of the parametric study are important in terms of residual horizontal displacement of the wall.

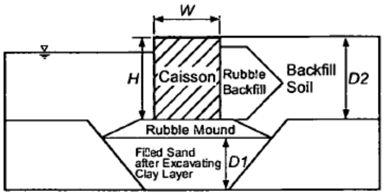

Fig1. Typical cross section of a gravity quay wall for parameter study

The wall that we studied has below conditions:

$$H = 16.5m \quad , W = 12m \quad , D1 = 8.5 \quad ,$$

$$N = 10 \quad , a = 0.54g$$

$$\frac{W}{H} = \frac{12}{16.5} = 0.73 \quad , \quad \frac{D1}{H} = \frac{8.5}{16.5} = 0.52$$

We obtain the normalized lateral displacement, d / H based on the above parameters and the Fig.2.

$$\frac{d}{H} = 0.12 \rightarrow d \approx 2m$$

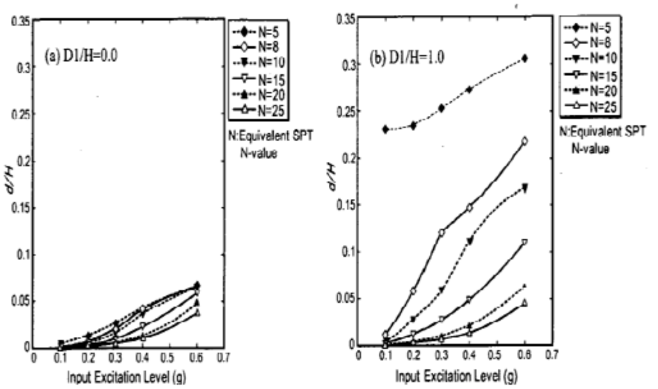

Fig2. Effect of input excitation level (for$W / H = 0.9$)

Seismic Performance of Gravity Type Quay Walls

Gravity type quay walls are made of a concrete caisson or other retaining placed on a foundation, sustaining earth pressure from backfill soil behind the wall. A typical failure mode due to earthquake is a seaward displacement and tilting of the walls for this type of quay walls. It depends on the foundation characteristics whether the damage involves overall deformation of the foundation beneath the wall. For example, a wall on a loose sandy foundation has a large seaward displacement. Because of seaward displacement of the caisson or retaining wall, settlements and cracks occur at the apron behind the wall.

Seismic performance of gravity quay wall can specify in term of serviceability. In addition, its serviceability depends on many factors such as settlements, displacement, tilting etc. In this paper, we consider that the damage criteria for gravity quay wall are seaward displacements at the top of the wall.

Case History

On January 17, 1995, one of the most disastrous earthquakes, called the 1995 Hyogoken-Nanbu earthquake of JMA Magnitude 7.2, hit the Hanshin area of Japan. Kobe Port was shaken with strong motion having peak ground acceleration of 0.54g and 0.45g in the horizontal and vertical directions. Port Island was been constructed between “1966-1981”. Its soil profiles are alluvial clay, caisson wall, backfill, foundation, and rubble in backfill & Foundation.

Most of quay walls in Kobe Port are of a rigid block type made of concrete caissons and were severely damaged by the earthquake. Quay walls moved about 5m maximum, 3m on average, toward the sea. The walls also settled about 1 to 2m and tilted about 4 degrees toward the sea. The damaged was caused mainly by deformation in the loosely deposited foundation soil beneath the caisson wall .The gravity quay wall is shown in Fig.3.

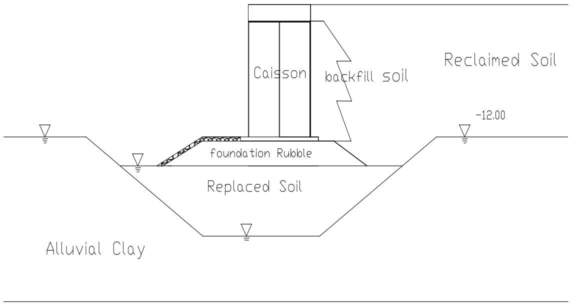

Fig.3. Cross section of quay wall (Kobe)

Finite element modeling

The finite element method was used for the analyses under the plain strain and undrained condition. This paper utility the finite element program of PLAXIS which has been demonstrated as applicable to the seismic analysis of gravity quay walls during the 1995 Hyogoken-Nanbu (Kobe) earthquake. PLAXIS is a finite element program for geotechnical applications in which soil models are been used to simulate the soil behavior. Geotechnical applications require advanced constitutive models for the simulation of the non-linear, time-dependent, and anisotropic behavior of soils and/or rock. A second goal is to compare the developing earth and water pressures with the conventionally applied Mononobe-Okabe and Westergaard pressures. This work is done within the framework of a case history from Kobe, involving the response of a quay wall in Port Island.

The cohesionless material in the backfill zone, the foundation zone, and the rubble zones that conclude foundation and backfill is modeled utilizing the elasto plastic constitutive model by Pastor et al. (1990). The clay zones are modeled approximately using the Mohr-Coulomb model with properly adjusted material parameters based on independent equivalent linear analysis. The seawater mass is modeled as a saturated, elastic sponge, having the density and the bulk modulus that is necessary as an elastic body, having an interface that allows slippage and separation at the base and the back of the caisson. 15-node triangular element, containing 12 stress points as indicated in Fig.4, was used. The model consists of a total 949 nodes in the FE mesh. The materials and their properties have listed in Table 1.

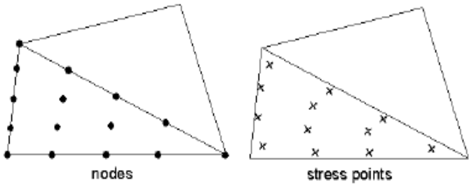

Fig4. Nodes and stress point

Table1.Material properties for model after Iai,et al., (1998) and Dakoulas and Gazetas,(2005)

Materials	clay	Backfill& Foundation	Caisson
Density (ton/m3)	1.7	2	2.1

Structural parameters of the concrete caisson are as follows: density, $\rho = 2.1$; shear modulus (KPa), $G = 1.3E7$; friction angle between foundation and caisson, $\delta = 31^0$; and friction angle between backfill gravel and caisson, 15^0.

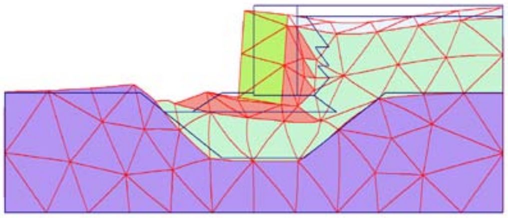

Fig5. Computed deformation at the end of earthquake

Fig.5 shows the post- earthquake permanent displacements of the finite element model with showing the deformed shape after the earthquake. One may observe from Fig.5 that there is a significant movement of a quay wall. It can be seen that significant tilting and seaward displacement of the wall has occurred. As the wall is rigid, its movement is due to the deformation of the foundation rubble, which creates a significant heave at the toe of the wall. The toe of the wall was placed on node number 496 in Finite element modeling.

Table2 .Results of PLAXIS

	Computed	Observed
Node	496	--
X(m)	25	--
Y(m)	28	--
X Displacement (m)	3.02	3-5
Y Displacement (m)	1.2	1-2

Horizontal acceleration was applied to the model and the results were compared with observed field measurements. At the end of earthquake shaking, horizontal and vertical displacement of the upper seaside corner of caisson is computed. The computed horizontal and the vertical displacement at the upper seaside corner of the quay wall was 3.3m, 0.59m that PLAXIS measured these displacements 3.02m and 1.20m.

The overall response in Port Islands is consistent with the observed behavior. After analyzing the reasons of displacement of upper seaside corner of caisson in Fig.5, it is seen that the Liquefaction occurred In the fill material that is unimproved in the free field.

The reason of this occurrence is the increase of the pore water pressure and decrease of shear strength. Due to excess pore water pressure increase, reduction in the bearing capacity of foundation soils was speculated to be the main cause of the damage to the caisson walls at Kobe port. The caisson moved toward the sea.

Horizontal and vertical displacement of the upper seaside corner of caisson is the damage criteria for gravity quay wall that are studied.

It should be also noted that the lateral spreading of soil near the areas influenced by the quay wall is clearly visible. In addition, differential settlement between the caisson and the apron as well as the deformation of the foundation rubble beneath the caisson is also observed in Fig.5. This is consistent with the actual mode of deformation reported by many investigators after the 1995 Kobe earthquake.

Although the sliding mechanism could explain the large horizontal displacement of the caisson walls, this mechanism does not explain the large settlement and tilting of the caissons.

CONCLUSIONS

Ports are very important nodes of national and international transportation networks and play a crucial role in economic activity of the nation. Among many types of port structures such as caisson type, block type, pile-supported type, and sheet pile type, the focus of this research is on the caisson type quay wall.

In this paper, a case study of quay wall damaged during the 1995 Hyogoken-Nanbu earthquake, is presented to evaluate the mechanism of the damage on quay walls and the influence of soil properties on the residual deformation of gravity quay walls during the earthquake. A model of Port Island quay walls was developed using a finite element software PLAXIS. Horizontal acceleration was applied to the model and the results showed good agreement with the observed field measurements.

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