Numerical modeling of seismic performance of gravity quay wall

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Abstract. The main important factor that has to be considered by the designers during the preliminarily design stage of quay walls in ports is understanding the mechanism of the damages that occurs during earthquakes. Increasing of seismic disasters occurrence during recent decades leads to increase the attention during this stage. For this purpose, Finite element modeling is performed to investigate the seismic performance of gravity quay wall (caisson). Plaxis 2D software is used to simulate seismic behavior of real gravity quay wall (i.e. Kobe harbor quay wall) using single frequency earthquake motion. The response of the acceleration and the seismic displacement of the quay wall are simulated. The shaking table tests of two models of the quay wall in dry and saturated conditions were compared with the results of numerical modeling. 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. It was observed that the Plaxis-2d finite element models is an effective tool to predict the seismic performance of the quay wall and there was clear agreement between both the results of experimental results and numerical modeling.

Keywords: numerical analysis, quay wall, Earthquake, Acceleration

1. Introduction

Very large damages are happened in coastal facilities (ports and harbors), such as those in reclaimed lands, during previous major earthquakes in Japan, 2001. Many quay walls after that event were lost because the quay walls of the caisson had been moved towards the sea due to occurrence of liquefaction in the backfill soil (the worst damage after the tsunami) and this phenomenon leads to increase the economic losses [1]. During Kobe earthquake in Japan and Chi-Chi earthquake in Taiwan, several of the quay walls displaced in the direction of the sea, also because of occurring liquefaction of the sand, which was fully saturated beneath and behind the walls due to significant increasing in the pore water pressure. In recent years, many of the various experimental and numerical approaches have been discovered for assessing the performance of ground and supporting structures under the effect of seismic loading including Situations where liquefaction is probably to happen [2]. Many previous studies focused on the seismic performance of quay walls experimentally, numerically and even in-situ assessment [3, 4]. The performance of quay wall type-caisson built on loose saturated sand t was tested by using 1-g shaking table tests [4]. It was observed that the soil of foundation having a major role in the seismic response of a wall-soil system. The performance of this kind of quay wall was assessed also by [5]using numerical and experimental approaches. It was emphasized that forecasting the behavior of a structure based on liquefiable soil during an earthquake depends greatly on appropriate accounting for the development of the pore water pressure during the seismic loads, stress-
strain softening and reduction of the strength in the soil on the system performance [6]. The seismic performance of gravity quay wall type (block quay wall) is tested analytically and numerically by means of a method of un-drained effective stress analysis including build-up of the pore water pressure because of dynamic loading [7-10]. This was achieved by using finite element analysis and it was noticed that the seismic behavior of the quay walls type gravity is greatly influenced by non-linear behavior of soil performance [11-13]. increasing of excess pore pressures and accumulating of the shear and volumetric strains both at the foundation soil and retained soil, generates shear strength deterioration which can contribute to liquefaction [14]. The dynamic response of multi-block gravity quay walls (i.e. seismic displacement, rotation, backfill response and block-sliding) has been investigate numerically using finite element models and verified experimentally using geotechnical centrifuge [15]. The results showed that the forecasted of numerical analysis higher displacement of the quay wall in the direction outward, followed by a level larger settlement to backfill than the centrifuge test. A probable reason for this discrepancy may be credited to the backfill and foundation soil densification after the first cycles of movement.

In this paper, gravity quay wall type caisson is modeled and tested numerically using Plaxis 2D finite element numerical modeling to investigate the seismic behavior of such structure (i.e. seismic displacement, acceleration response). The results were compared with experimental outputs (shaking table tests) that were tested before by [16].

2. Numerical Modeling
In recent decades, there has been a major development in the field of commercial computer software packages used in the process of analysis, assessment and design of different structural projects. Some of these techniques are specialized in used in the seismic analysis of quay walls. The analysis in many of these commercial computer programs is based on the numerical modeling in two different ways, namely a finite difference analysis method and the finite element analysis method. Numerous complicated problems can be solved by using these commercial computer programs, For instance, the analysis of the seismic response of the gravity quay wall, the analyzing of the fluid-structure-soil interaction mechanism and the discovering of the seismic displacement of the gravity quay wall as well as the determination of the dynamic loading factors can be investigated very well without time consuming. The most common way is surely is the finite element which is considered a comprehensive way to evaluating the behavior of soil structures influenced by earthquake action and has some advantage when considering the natural processes of failure, the soil-structure interaction. In this study, the computer program PLAXIS V8.5 is used. The dynamic model in this program is limited to plane strain and axisymmetric conditions. A non-linear analysis of the history of time-acceleration was conducted. The seismic performance of gravity quay wall would be assessed due to the displacements and the dynamic amplification of acceleration measurements obtained from the PLAXIS V8.5 software.

2.1 Constitutive Model
The gravity quay wall model type caisson is drawn as shown in figure 1 with scale down equal to 1/50 of a typical prototype in the Rokko island and port island [17]. It is modeled and analyzed using finite element program PLAXIS 2D version 8.5. The analysis has been performed taking account material (in soil) and geometric (interface) non-linearity. The modeling process for the soil and quay wall was done by using plane strain element with fifteen-node. The prescribed displacement was imposed in the horizontal direction to prevent movement in the vertical directions. The contact area between the gravity quay wall model and the soil has been modeled using special interface elements. Figure 1 shows the model geometry. The model dimensions are in m and the unit of time is (sec) since dynamic effects are usually in the order of seconds rather than days. Standard fixity, which is used to simulate the model in reality are applied to the model as well as the absorbent boundaries that were applied as a special condition to absorb waves arrive the external limit of the model.
2.2. Material properties of the model

To predict the performance of the gravity quay wall type caisson, an appropriate soil model and suitable design properties of the material (soil and concrete) have been defined as input parameters. Soil has been the most complex material and various types of material models can be applied to the solution of geotechnical problems during analytical and numerical analysis. The soil available models in the PLAXIS software program are the linear elastic model, the Hardening soil model, the soft soil model, the Mohr-Coulomb model, the soft soil creep model and the articulated rock model. Selecting of the appropriate model was based on the model material presented in table 1. The layers of sandy soil and the filter zone were modeled as the hardening soil model which was selected as specified in Plaxis as described clearly in the software manual [18] under dynamic loading and a linear-elastic stress-strain behavior for the retaining walls was assumed using appropriate value of Young module (significant) to simulate a rigid gravity quay wall. The body of the quay wall is already constructed from of concrete material which is modeled here using a linear elastic model taking into account non-porous behavior.

### Table 1. characteristics of material of the subsoil and the quay wall body.

| symbol          | parameters             | units           | Hardening soil | Linear elastic (quay wall body) |
|-----------------|------------------------|-----------------|----------------|---------------------------------|
| \( \gamma_{unsat} \) | Unsaturated unit weight | kN/m\(^3\)      | 20             | 16                             | 24                             |
| \( \gamma_{sat} \)  | Saturated unit weight  | kN/m\(^3\)      | 22             | 19                             | 24                             |
| \( E_{50\,ref} \)  | Reference secant young’s models | kN/m\(^2\) | 150000         | 20000                          | 40000                          |
| \( E_{oed\,ref} \) | Reference constraint modulus | kN/m\(^2\) | 148244         | 20000                          | -                              |
| \( E_{ur\,ref} \)  | Reference unloading - reloading modulus | kN/m\(^2\) | 450000         | 600000                         | -                              |
| \( \phi \)         | Shear strength angle   | degree          | 45             | 40                             |                               |
| \( \psi \)         | Dilatancy angle        | degree          | 15             | 10                             |                               |
| \( v_{ur} \)       | Passion ratio          | -               | 0.2            | 0.2                            | 0.2                            |
| \( p_{ref} \)      | Reference stress       | kN/m\(^2\)     | 100            | 100                            | -                              |
| power             | Power for stress level dependency | -               | 0.5            | 0.5                            | 0.5                            |
| \( k_{o\,nc} \)    | Earth pressure coefficient at rest | -               | 0.31           | 0.36                           | -                              |
| \( R_F \)          | Failure ratio          | -               | 0.9            | 0.9                            | 0.9                            |

2.3 Mesh generation

Meshing plays a major role in obtaining a realistic output in the dynamic analysis process. The mesh generation in Plaxis is completely auto and mainly focuses on a robust triangulation system leading in
an unstructured mesh. In Plaxis, 6-noded or 15-noded elements for automatic meshing can be applied. In this paper, a 15-noded triangular element is selected for the analysis because of their accuracy rate and increased capability to capture stress concentrations. For the present problem, figure 2 Shows the typical meshing.

![Figure 2. Typical meshing configuration of quay wall model.](image)

2.4 Input motion

The input motion used in numerical modeling having an amplitude 0.8g with duration 10 sec as shown in the figure 3, which represents twice the magnitude of Tokachi Oki, Japan in 2003 earthquake and pam, Iran in 2002[1]. This destructive magnitude is selected to simulate the input motion of shaking table tests that were performed by [16] to see how the numerical will verify the experimental results.

![Figure 3. The used input motion in the numerical modeling analysis.](image)

3. Results of Numerical Modeling

The used input motion in numerical modeling in the program is the same as the input motion used in the testing of the shaking table in the experimental work as described above so that the calibration between laboratory results and numerical modeling is more realistic. For predicting the time histories of acceleration that was obtained from the distributed accelerometers positions in the shaking table models and the LVDTs (i.e. cyclic displacement and the settlement that were measured experimentally), four main points located as (a, b, c, d) were selected as illustrated in the figure 4 to predict the acceleration, the vertical and the horizontal displacement to cover the whole seismic performance of gravity quay wall as inspected in the experimental models.
3.1 Predicted Acceleration
The results of the acceleration that were obtained using finite element PLAXIS 2D are showed in figure (5). The results showed an attenuation with acceleration measured at point (b) when compared with measured acceleration at point (a), this due to the effect of the weight of the wharf wall model, which in this case acts as a damping of the soil movement, but there was an amplification of the measured acceleration at the crest of the quay wall model, this caused by the effect of the cyclic wave pressure of water in the face of the waterside of quay wall model.

It can be seen from figure above that very well prediction is obtained and the amplification due to the wave propagation from the bed of the model to the crest of the quay wall is well captured (i.e. Acc. 1).

3.2 Predicted dynamic horizontal and vertical displacement
Figure 6 showed that the predicted dynamic horizontal displacement and dynamic vertical displacement (settlement). The horizontal displacement was in the positive direction only, meaning
that the model movement was towards the backfill soil and dynamic vertical displacement appeared in
the negative direction only which replicated the settlement of the quay wall. This can be attributed to
the fact that the dynamic water wave was so great during shaking and leads subsequently the failure
shape to be as a backward rotation because the shear failures of rubble mound layer and soil
foundation in a back toe of quay wall model. It can be noticed that the horizontal displacement has
actually started increases gradually at time t = 0.93 sec for both the shaking table model and the finite
element model (see input motion at this time), which is the same time at which the model starts the
actual vertical displacement (settlement).

Figure 6. Predicted displacement; (a) horizontal
displacement and (b) vertical displacement (settlement).

From Figure 6a, it is very clear that the horizontal displacement from finite element model has
trend similar to that measured from the shaking table test, except the cyclic shape. Actually, the cyclic
horizontal displacement has not been well captured and this is due to Rayleigh damping factor that
have been used in the finite element model which prevent the shape of the displacement to be
appeared as in case of the experimental. In contrast, the vertical displacement (settlement) is very well
simulated and because the
is no cyclic vertical settlement due to huge weight of the structure as
shown in figure 6b (i.e. quay wall)

4. Conclusions
This paper focuses on using numerical modeling technique (using Plaxis-2D software) for study the
dynamic performance of gravity quay wall. This was carried out by simulating the gravity quay wall in
reality and the seismic results were compared with data obtained from shaking table tests. The major
conclusions are summarized below:
1. The acceleration and the displacement of the literature study (i.e. shaking table tests) are well
captured particularly in term of the dynamic amplification at the crest of the slope.
2. The results showed that the seismic acceleration amplification is increased significantly at the crest of quay wall model but there is attenuation at the foundation soil layer, this due to the effect of quay wall model weight which works as damping for the foundation soil beneath the quay wall model.

3. The finite element model can be used in the preliminary design during assessment of the dynamic response of the proposed structure based on the time-acceleration histories that can be obtained from any seismic station close to the site.

4. The predicted dynamic horizontal displacement was only in the positive direction due to the effect of shaking intensity and seismic wave of water from the waterside of the quay wall model and the settlement of quay wall model was only in the negative direction.

5. Based on the obtained results of the displacement and the time-acceleration from the numerical modeling using Plaxis-2D, it can be said that the Numerical technique is an influential tool to predict the seismic performance of the quay wall model.

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