Assessment of Seismic Displacement of Quay Walls

K. Pushpa, S. K. Prasad, and P. Nanjundaswamy

1 Introduction

Quay walls are the basic elements of any marine structure and form basic elements of infrastructure. Despite the advances in earthquake geotechnical engineering, there have been many failures of port structures during strong earthquakes. Damage to these structures results in serious economic and physical consequences. The typical seismic failures usually are lateral sliding, overturning, and settlement of quay walls leading to port facilities being non-functional for a long time. Hence, a lot of insight is necessary for the performance of these structures. Port structures that were subjected to strong earthquakes at Niigata (1964), Tokachi-Oki (1968), Nemuro-Hanto-Oki (1973), Kushiro-Oki (1993), and Hyogoken Nanbu (1995) had been designed employing seismic coefficients whose values were about half the values of the peak accelerations actually experienced during the earthquakes (Pianc 2001). Even though the design was so similar to the actual conditions, the extent of damage was very severe. The damage was observed to be dependent on the liquefaction of the soil in the surrounding region which was highest during the Hyogo-ken-Nambu and Niigata earthquakes. It clearly indicates that the effect of liquefaction at site and pore pressure build-up have a high impact on the performance of port structures.

K. Pushpa (✉)
Department of Construction Technology & Management, J.S.S. Science & Technology University, Mysuru 570006, India
e-mail: pushpa_k@sjce.ac.in

S. K. Prasad
Vidyavardhaka College of Engineering, Mysuru 570006, India
e-mail: skprasad@vvce.ac.in

P. Nanjundaswamy
Department of Civil Engineering, J.S.S. Science & Technology University, Mysuru 570006, India
e-mail: pnswamy@sjce.ac.in

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The very existence of water alongside the retaining walls influences the magnitude of seismic pressure on it. The liquefaction of backfill soil of port structures is one of the major damages caused due to the occurrence of earthquakes, may it be moderate or strong.

Various researchers Al-Homoud and Whitman [1], and various others have conducted numerical analysis on retaining walls subjected to dynamic earth pressures. Choudhury and Chatterjee [5] made use of the experimental results to verify that the seismic active earth pressure distribution relies on the type and amount of wall movement. Nanjundaswamy et al. [12] have employed the use of finite element software FLAC to model and analyze the seismic performance of quay walls. Richard-Elms gave the design of retaining walls on the basis of allowable permanent displacement of the retaining walls. All these studies on retaining walls show that the design of retaining walls based on allowable displacement reduces the extent of the damage.

2 Analysis of Displacement of Quay Walls

The factors responsible for the performance of water retaining structures are mainly backfill and foundation soil properties, geometry of the wall, boundary conditions, groundwater level, characteristics of earthquake motions, and more. A typical Quay wall with properties as mentioned in Table 1 is modeled using the software. These properties are used as input parameters in the software.

A typical quay wall modeled using Quake/w feature of GeoStudio software is as shown in Fig. 1. It consists of a retaining wall constructed on a foundation of dense sand and a backfill composed of loose sand on one side and seawater on the other side. The boundary conditions are taken as fixed X along with the depth of foundation and backfill and fixed XY along the length of the foundation are specified. The presence of water outside the retaining wall will impose a dynamic pressure on the face of the retaining wall, while the presence of water in the backfill soil adds on the dynamic pressure on the back of the retaining wall. There is a cyclic loading due to the water pressure. Westergaard [15] gives a method to estimate the hydrodynamic pressure.

In addition to the lateral earth pressure and the hydrodynamic pressure on the quay wall, a ground motion due to the earthquake is applied. Considering the ground motion waves as sinusoidal with a frequency of 1 Hz and peak ground acceleration varying from 0.05 to 1 g the analysis is conducted. The various parameters attributed to the deformation or permanent displacement of the quay wall are studied.

3 Parametric Study

The various parameters which influence the permanent displacement of the wall studied here are amplitude of acceleration of ground motion and liquefaction of

Table 1 Properties of backfill and foundation soil

Property	Units
Backfill soil properties	
Unit weight	16 kN/m^3
Angle of internal friction	30^0
Cohesion	0
Damping ratio	0.6
Poisson's ratio	0.25
Coefficient of lateral earth pressure, K_o	0.5
Foundation soil properties	
Unit weight	20 kN/m^3
Angle of internal friction	40^0
Cohesion	0
Damping ratio	0.6
Poisson's ratio	0.25
Coefficient of lateral earth pressure, K_o	0.5
Quay wall properties	
Unit weight	24 kN/m^3
Shear modulus, G	21GPa
Height of the wall	8 m
Width of the wall	6 m

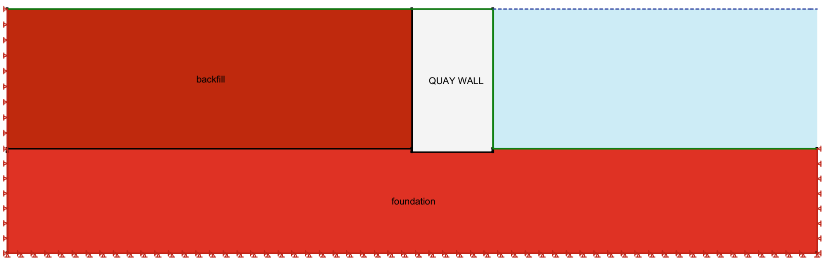


Fig. 1 A typical quay wall model with backfill soil, foundation, and seawater

backfill soil. Mononobe–Okabe's equation [11] and Westergaard's equation [15] are used to calculate seismic earth pressure and dynamic water pressure on a retaining wall. The backfill soil and water system shows movement along the base of the retaining wall when the ground acceleration is greater than yield acceleration.

Richard-Elms gave a method of calculating the allowable or permanent displacements in the same way as that of the Newmark sliding block method as

$$d_{perm} = 0.087\frac{v_{max}^2 a_{max}^3}{a_y^4} \tag{1}$$

Towhata and Islam [13] gave a method to estimate the displacements of retaining walls by employing Newmark's sliding block theory. Towhata (1993) proposed another type of simplified method to predict the permanent displacement of gravity type quay walls.

In order to analyze the allowable permanent displacement, the present study employs the use of a model of quay wall developed using quake/w feature of finite element software GeoStudio. The methodology behind the calculation of displacement in Quake/w is double integration of the acceleration versus time increment record. The strain components are related to x and y displacements, u and ν, as follows:

$$\varepsilon_x = \frac{\partial u}{\partial x} \tag{2}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} \tag{3}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \tag{4}$$

3.1 Boundary Effect

It becomes essential to ensure that the length of the analytical model is sufficient such that the fixed boundary does not alter the response of an infinitely long system in the middle region. For a relatively long model, it can be assumed that the deformation of soil in the central region of the model is close to that of the prototype with infinite boundaries. The physical or numerical model has restricted length, but represent infinite length or field. Hence, the focus of preparing the model is to plan such infinite physical length which does not alter the behavior of the quay wall region. Hence, arbitrarily in Table 2, length beyond quay wall till the boundary ranging from 6 to 41 m were tested and it was found that 256.5 m on either side of quay wall as

Table 2 Variation of horizontal displacement with an increase in length of foundation

Length of foundation (m)	Displacement (m) (before liquefaction)	Displacement (m) (after liquefaction)
15	0.930	2.12
31	0.879	2.10
48	0.870	2.17
56	0.874	2.20
64	0.873	2.20
85	0.871	2.01

Table 3 Variation of displacement of quay wall with an increase in mesh size

Mesh size (m)	Displacement (m)
0.2	0.69
0.5	0.69
1.0	0.70
1.5	0.70
2.0	0.71
2.5	0.70

shown in Fig. 1 was sufficient. Hence, the foundation length is varied in order to study the boundary effect on the analytical model as shown in Table 2.

The above observations indicate that there is an increase in the displacement after liquefaction compared to that before liquefaction. But, the changes in displacement before and after liquefaction with an increase in the foundation length are insignificant, and hence the boundary effects are taken care.

3.2 Convergence Check

Discretization or meshing is one of the fundamental aspects of finite element modeling besides defining boundary conditions and material properties. Discretization involves defining the geometry, distance, area, and volume of the mesh. GeoStudio ensures mesh compatibility within a region and for the most part ensures mesh compatibility across adjacent regions, but it is still possible to create a situation whereby mesh incompatibility exists. Table 3 shows the variation of displacement of quay wall with an increase in mesh size.

It can be observed that the increase in mesh size does not have a measurable impact on the values of displacement and hence the convergence effect is taken care of.

3.3 Effect of Acceleration of Ground Motion on Quay Walls

Before liquefaction of backfill soil

From the study of earthquake records, it is found that the predominant frequency of most of the earthquakes that cause severe damage were in the range of 1 to 3 Hz and peak average amplitude of acceleration was around 0.5 g. [2]. Hence, in the present analytical study, the amplitude of ground acceleration is varied from 0.05 g to 1 g at a frequency of 1 Hz. The magnitude and frequency of acceleration have a direct impact on the lateral displacement of the quay walls. Quake/W computes the displacement by double integration of the acceleration versus time increment record.

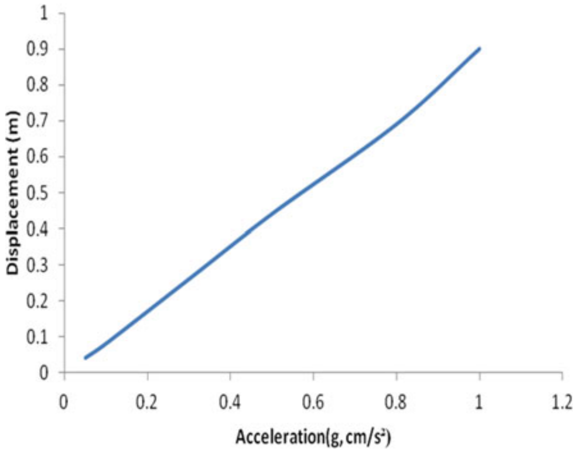


Fig. 2 Variation of horizontal displacement of quay wall with change in acceleration

Figure 2 shows a linear variation of displacement with an increase in the magnitude of the acceleration of ground motion when the backfill is not liquefied.

After liquefaction of backfill and foundation soil

The most widespread source of damage due to an earthquake on the port facility has been the liquefaction of loose, saturated, and sandy soils. It has been observed over the years that significant liquefaction and ground movement and damages have not only occurred under very strong ground movements, but under moderate shaking also. Since the backfill soils are usually cohesionless, there are higher chances of liquefaction even under moderate earthquake motion. As a result, the modes of failure of the quay walls are usually lateral sliding, settlement, and rotation.

The sliding displacement of the quay wall when the backfill liquefies is analyzed by the analytical approach. The observations are presented in graphical form in Fig. 3.

It can be observed that the sliding displacement increases exponentially with the increase in the horizontal acceleration of ground motion. The magnitude of displacement is higher than the case without backfill liquefaction by several folds.

4 Comparison of Analytical Test with Model Test Results

In an earthquake, geotechnical engineering model testing is one of the important methods of recreating the field scenario in the laboratory. Model studies give a path to procure special data like excess pore pressure changes, flow of liquefied ground, and amplification in ground motion. Both practical and theoretical investigations are necessary to understand the problems linked with seismic failure of quay walls considering the complexities and uncertainties involved. It is essential to evaluate the true mode of the wall movement and impact of liquefaction both in backfill and foundation soil regions.

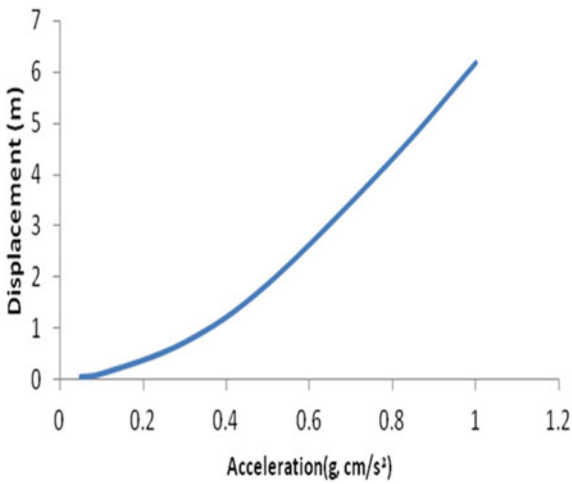


Fig. 3 Variation of sliding displacement of quay wall with the acceleration of ground motion

The details and results obtained from model tests on the shaking table conducted by Nanjundaswamy [12] as a part of his Doctoral thesis are compared with those obtained from the finite element software. Model studies were conducted at normal gravitational environment (1-g test). The transparent model container and manual shaking table developed at Earthquake Engineering Laboratory of S. J. College of Engineering, Mysore, is shown in Fig. 4.

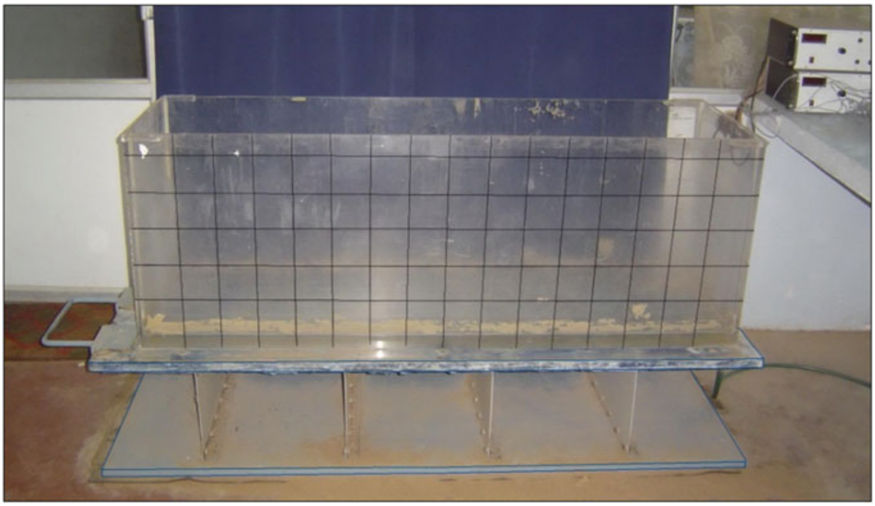


Fig. 4 Assembly of manual shaking table with a transparent model container

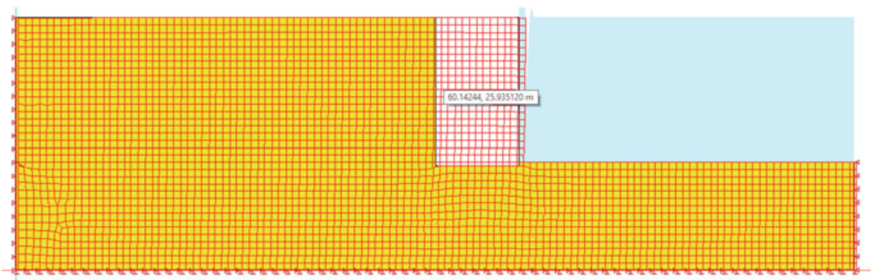
Table 4 Comparison of sliding displacement of quay wall from the physical model test with that from the present analytical study

Sl no	Type of test	Horizontal sliding displacement (mm)
1	Model test in laboratory	80
2	Present Numerical study using Finite element analysis	66

The materials that are used as well as the size of the shaking table used in the shaking table play a major role in the ground motion study. The configuration and dimensions of the manual shaking table used are as detailed below [12].

- Two wooden panels 600 mm wide, 1800 mm long, and 25 mm thick were used such that one of them formed the base and the other acted as a platform.
- Four steel plates 350 mm long, 550 mm wide, and 2 mm thick were provided to act as springs.
- The connections between plates and wooden panels were provided through steel bolts and angle sections.
- A handle was provided at the end to apply harmonic sinusoidal input force along the longitudinal direction.
- Rubber membranes of 3 mm thick were provided between the floor and table and model container and table in order to prevent relative slip between the components.
- Shaking table was designed to vibrate at around 2 Hz. with 0.5 g level of acceleration at a payload of around 7 kN.
- The overall cost for the assembly of the entire shaking table did not exceed Rs. 10,000/- at the time of fabrication.

Table 4 presents the comparison of sliding displacements obtained from the physical model test with that of the numerical model using the Finite Element approach in the present study. In both the cases, similar conditions such as dense foundation soil, loose backfill and medium-heavy quay wall were considered.



The results from the analytical model obtained from quake/w model as shown above indicates that the quay wall is displaced by 66 mm while the model test results show that there is a sliding displacement of 80 mm of the quay wall. There is a considerable closeness in both the approaches.

5 Conclusions

1. The study conducted from Quake/w module of finite element software Geostudio shows that the effect of liquefaction of backfill has a pronounced effect on the permanent displacement of the quay wall.
2. The finite element software GeoStudio serves as an effective tool in the analysis of the performance of quay walls during an earthquake.
3. The amplitude of acceleration of ground motion has a considerable impact on the performance of quay wall, especially when the backfill liquefies.
4. The results obtained by the analysis of the model developed using the finite element software are comparable with those of model tests conducted using the shaking table with similar properties of backfill and foundation soil, and quay wall.

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