Seismic dynamic response analysis of permeable breakwater on piled foundation considering pile-soil interaction

Duohan Zhang¹,², Jinsong Gui¹,²,*

¹ College of Ocean and Civil Engineering, Dalian Ocean University, Dalian Liaoning 116023 China
²1104793748@qq.com, bguijs@163.com (*corresponding author)

Abstract. In order to discuss the seismic response of pile foundation permeable breakwater structure under different working conditions, the dynamic implicit module in finite element software ABAQUS is used to analyze the seismic dynamic response of pile foundation permeable breakwater. Considering the nonlinear characteristics of pile-soil interaction the breakwater is simulated under different seismic intensity conditions. The acceleration, bending moment of pile foundation are analyzed by time-history analysis method. The influence of pile diameter on the whole structure is compared. The results show that the stronger the earthquake is, the more obvious the overall dynamic response of the structure is. The bending moment of pile body decreases first and then increases. The wider the diameter of pile foundation, the greater the stiffness of the whole structure, resulting in an increase in the seismic force received by the structure. Compared with the static load, the influence of earthquake on the permeable pile breakwater can not be ignored.

1. Introduction
Permeable breakwater on piled foundation is a new type of breakwater structure. It has a simple structure, low material consumption and low cost. At present, the research on the dynamic response of the Permeable breakwater on piled foundation mainly uses the physical model test method, but the numerical simulation test method is less studied, but the latter is applied in the similar high-pile wharf structure. Donahue[1] used the 3D model established by SAP2000 to analyze the response of the 24/25 berth in the Port of Oakland under the Loma Prieta earthquake. Li Ying and Gong Jinxin[2] used ABAQUS software to analyze the seismic response of high-pile wharf based on the material nonlinearity of soil and structure, and studied the mechanism of internal force and plastic hinge formation of pile foundation. Mageau et al[3] used PLAXIS 2D software to analyze the seismic response of the new dock in Tacoma Port, USA, and found that ground treatment is needed to reduce the foundation deformation and pile bending moment to meet the performance standards recommended by the specification. Ayothiraman[4] conducted a dynamic test on single pile model aluminum piles in different consistency clays, and studied the bending behavior of single piles under lateral loads.

In this paper, based on the finite element software ABAQUS, the finite element model of the pile-based transparent breakwater is established. The dynamic response of the structure under different earthquake strengths is analyzed. It provides reference for the design of pile foundation permeable breakwater structure.
2. Model establishment

2.1 Project Overview

The sectional view of the permeable breakwater on piled foundation in a certain port area is shown in figure 1. The upper pile platform structure is beam-slab structure, with a width of 15m and lateral bent spacing of 3.8m. Each standard segment is composed of 3 lateral bents, with 3 beams and 5 longitudinal beams (wall beams on both sides). The rock-socketed pile with a diameter of 1.2m and a pile length of 12.3m is adopted at the bottom of the beam. The bearing stratum at the pile end is tuffaceous layer.

2.2 Establishment of finite element model

Based on the symmetry of the breakwater along the bank and the direction of seismic excitation, a typical 15m bent is analyzed to establish a finite element model of the permeable breakwater on piled foundation shown in Figure 2. The model size is 75m×15m×35m, 10 3180 units, the three-dimensional solid element C3D8R is used for the breakwater and the near-field soil, and the infinite unit CIN3D8 is used for the far-field soil. The width of the soil is 3 times the width of the levee and the depth is 2 times.

Tie contact is adopted between the upper panel of the structure and the transverse longitudinal beam, the beam and the top of the pile, and the main-slave contact is used to simulate the pile-soil.

2.3 Material parameters and boundary conditions

The panel, the wave shield, the beam and the longitudinal beam are all made of C35 concrete, and the rock-socketed pile is made of C50 concrete. The soil is the ignimbrite. The Mohr Coulomb strength model is adopted. The breakwater adopts a linear elastic constitutive model. The damping selection applies Rayleigh damping. The specific parameters are shown in Table 1.

Table 1. Physical and mechanical parameters of materials

| Parameter name | Density (kg/m³) | Elastic Modulus (GPa) | Friction angle (°) | Cohesion (kPa) | Poisson's ratio | Damping ratio |
|----------------|-----------------|-----------------------|-------------------|---------------|----------------|--------------|
| C35 concrete   | 2400            | 32.5                  |                   | 0.2           | 0.04           |
| C50 concrete   | 2500            | 34.5                  | 40                | 1200          | 0.35           | 0.02         |

This paper uses the infinite element with good wave energy absorption to deal with the reflection problem of the wave. The infinite element boundary is set in front and rear of the soil body. The left and right sides are provided with the chain bar constraint perpendicular to the corresponding plane, and the bottom is set as the fixed constraint.
2.4 Contact settings
The contact area between the pile and the soil adopts the principal-slave surface contact to simulate the phenomenon of bonding, sliding and detachment between the pile and the soil. The Coulomb friction model is used to describe the friction characteristics of the contact surface in the tangential direction of the contact surface. The ultimate shear stress $\tau_{\text{crit}}$ when the contact surface appears relative slip can be expressed as

$$\tau_{\text{crit}} = \mu \sigma_n$$

among them $\mu$ For the coefficient of friction, this paper takes $\mu = 0.5$ tangential behavior is simulated using a penalty function. When the contact surface creates a gap, the normal pressure between the contact surfaces will not be transmitted, so the normal interaction between the contact surfaces in this paper adopts the hard contact method.

2.5 Initial conditions and input of seismic waves
Balanced geostress is a very important part of geotechnical calculation. By defining the initial stress in the initial field, it is ensured that the soil has been consolidated under gravity and there is no relative slip between the piles. In this paper, the ODB introduction method is used to achieve the order of magnitude $10^{-6}$ of soil displacement after the balance of ground stress by repeatedly iterating the results.

In this paper, the input direction of the seismic wave is horizontal, using a typical El-Centro wave, see Figure 3. In order to improve the calculation efficiency, the significant band 0–16s is selected. According to the specification, the spectral characteristics are kept unchanged, and the acceleration peaks are adjusted to 0.1g, 0.2g, and 0.4g, respectively corresponding to the seismic intensity of 7 degrees, 8 degrees, and 9 degrees.

When the infinite element is used as the boundary of the soil, the input of the seismic wave in the form of acceleration will cause the structure to drift. When the displacement time history is selected as the input mode, the drift of the structure can be reduced. In this paper, the seismic acceleration curve is integrated to obtain the displacement time history curve, and then the baseline correction is performed. The corrected displacement time history curve is input at the bottom boundary of the soil model. The displacement time history curve is shown in Figure 4.

![Fig. 3 El-Centro wave curve](image1)
![Fig. 4 Input displacement time history curve](image2)

3. Calculation results and analysis

3.1 Panel dynamic response analysis
Figure 5 and Figure 6 show the acceleration response and displacement time-history curve of the panel under the action of horizontal seismic waves. It can be seen that the horizontal acceleration of the panel increases as the seismic intensity increases. Compared with the previous level, the peak acceleration under the action of various seismic waves increases by nearly 180%. On the one hand, it is due to the amplification of seismic waves by the soil. On the other hand, since the vibration of the structure is related to the natural frequency and the external load, the natural frequency of the structure is 0.32 s, which is closer to the frequency of the seismic wave, and it is easier to excite the vibration of the structure. In order to avoid the structure from generating a large resonance under the action of seismic
waves, the structural form can be changed to appropriately reduce the stiffness.

Fig. 5 Acceleration time history curve     F i g .  6  D i s p l a c e m e n t  t i m e  h i s t o r y  c u r v e

3.2 Analysis of bending moment of pile body bending moment

Figure 7 is the peak curve of the bending moment of the first row of piles on the side of the wave. The peak value of the bending moment increases from the bottom of the pile to the original mud surface and then increases. The maximum value of the negative bending moment is reached at -5.3m, and then the bending moment increases sharply. The peak bending moment of pile body is still a process of decreasing and then increasing from the mud facial line to the pile top, reaching the minimum positive bending moment at 4.8m, then gradually increasing, and reaching the maximum positive bending moment at the pile top.

Figure 8 shows the peak acceleration curve of the pile body. The effects of different seismic waves on the acceleration of the pile body are quite different. The acceleration of the pile under the action of 0.1g seismic wave is small. The peak acceleration of the pile below the mud line is close to the peak value of the input seismic wave acceleration, indicating that the pile body is restrained by the soil at this time. Obviously, the soil piles are in close contact with each other. The effects of 0.2g and 0.4g seismic waves are more obvious, and the peak value reaches 19.01$\frac{m}{s^2}$ under the action of 0.4g . The contact between the piles creates a partial gap or slip.

Fig. 7 Peak bending moment curve          F i g .  8  P e a k  a c c e l e r a t i o n  c u r v e  o f  p i l e  b o d y

3.3 Influence of pile diameter

The diameter of the pile body was changed to 0.8m, 1.2m, 1.5m, and the displacement and acceleration of the whole structure under different diameters were analyzed when the seismic acceleration was 0.2g. It can be seen from Fig. 15 that as the diameter of the pile body decreases, the fluctuation range of the displacement value of the panel becomes larger and larger. Figure 16 shows that in the range of 0-4s, the difference of acceleration fluctuation range is not obvious; after 4s, With the decrease of pile diameter, the fluctuation range of acceleration increases, the period of curve increases, and the time of peak acceleration appears lags. It shows that the diameter of the pile body is reduced, the overall stiffness of the structure is weakened, the natural frequency of the structure is reduced, and the period is increased. Earthquake loads can be expressed as

$$ F_{eq} = ku = \omega^2 mu $$
The maximum seismic load of the pile body with a diameter of 0.8m is 133.76KN, and the maximum seismic load of 1.5m is 370.37KN. The decrease of the diameter of the pile body leads to the increase of the displacement of the whole structure. However, due to the increase of its natural vibration period, the seismic force on the whole structure is weakened. The diameter of the pile body has a great influence on the seismic performance of the breakwater structure. Reasonable selection of structure type can reduce the damage to the structure, reduce the cost, and give full play to the seismic capacity of the structure.

Fig. 9 Displacement time history curve     Fig. 10 Acceleration time history curve

4. Conclusions
Through the seismic numerical simulation analysis of a pile foundation transparent breakwater, the displacement and acceleration of the panel under different seismic loudness, the bending moment of the pile foundation, the shear force and the principal stress of the beam longitudinal beam are obtained. The pile foundations of different diameters are compared and analyzed. The impact on the overall structure leads to the following conclusions:

1. Under the action of seismic waves, the pile top position has the most obvious dynamic response, and the bending moment and shear force are relatively large. Therefore, special attention should be paid to whether the breakwater meets the material strength requirements and avoids the generation of plastic hinge in the seismic design.

2. The displacement and acceleration of the whole structure increase nonlinearly with the increase of seismic wave intensity.

3. The larger the diameter of the pile body, the larger the natural vibration frequency of the structure and the smaller the displacement, but the earthquake load is increased. Within the specified displacement limits, the stiffness of the structure should be appropriately reduced to avoid the natural vibration frequency of the structure close to the seismic wave frequency, the size of the reasonable design structure, and the damage to the structure caused by the earthquake.

References
[1] Donahue, M. J., Dickenson, S. E., Miller, T. H., & Yim, S. C. (2005). Implications of the observed seismic performance of a pile-supported wharf for numerical modeling. Earthquake Spectra, 21(3), 617-634.
[2] Li Ying, & Gong jinxin. (2010). Nonlinear seismic response analysis of piled wharf considering pile-soil interaction. Hydro-Science and Engineering, 2010(2), 92-99.
[3] Mageau, D. W., & Chin, K. H. (2007). Finite element modeling of new marine terminal at the port of Tacoma. In The Eleventh Triannual International Conference: Ports 2007, 30 Years of Sharing Ideas... 1977-2007American Society of Civil EngineersPermanent International Association of Navigation Congresses.
[4] Ayothiraman, R., & Boominathan, A. (2013). Depth of fixity of piles in clay under dynamic lateral load. Geotechnical and Geological Engineering, 31(2), 447-461.
[5] Hou-Qun Chen. (2006). Discussion on Seismic Input Mechanism at Dam Site. Journal of Hydraulic Engineering, 37(12), 1417-1423.