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Research on a Method for Simulating Hydrodynamic Pressure of Two-way Water Retaining Thin Plate

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Abstract. Under the action of an earthquake, the interaction between water bodies and solids is an important part of analyzing the stability of water retaining structures. This paper proposes the use of shell elements to simulate two-way water retaining thin plates, and the correctness of the method is verified by ANSYS fluid-solid coupling plate; then the new method is used to simulate the impact of the water on the thin plate under the action of earthquakes. Earthquake water pressure is used to analyze the seismic response law of the two-way water retaining plate. The research results show that: the hydrodynamic pressure of the two-way water-retaining sheet is greater than that of the one-way water-retaining, and is approximately equal to the sum of the dynamic pressures of the two-way water-retaining.

1. Introduction

A large number of water retaining structures are operated in the water, such as gates and ships. These structures cannot avoid the interaction with the water body when they are operating in water. The panels of the gate are in direct contact with the upstream and downstream water bodies. When the gate is running in the water, it directly interacts with the water body to generate vibration; on the other hand, a large number of hydraulic gates are located in the southwest region where high-intensity earthquakes occur frequently, and the designed seismic intensity is as high as Ⅷ or Ⅸ degree, the gate may also be affected by earthquakes during operation, and ground motion water pressure becomes one of the important design loads[1]. The vibration problem of the stern structure of ships has always received extensive attention. Because it runs in water, the impact of the water body on the structural vibration needs to be considered when analyzing the vibration.

The traditional method to simulate water bodies is Westergaard additional mass method[2]. The additional mass method originated from the calculation of the hydrodynamic pressure of the dam. The research problem is attributed to the fluctuation of the rigid wall at the semi-infinite liquid interface, ignoring the influence of the dam-water coupled vibration[3-4]. The result of using the additional mass is larger than the true value, especially the elastic structure of the thin plate, the error is often relatively large. The other is to simulate the effect of the one-way water body of the gate through the method of potential fluid. This only considers the effect of the one-sided hydrodynamic pressure of the gate. Consider that the upstream water body may be inconsistent with the actual situation[5].

Therefore, this paper proposes a new method to simulate the dynamic water pressure of the two-way water retaining thin plate to achieve more accurate simulation results to meet engineering needs.

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2. Basic equation

The fluid-solid coupling problem is to study the interaction between fluid and solid two-phase medium. The solid deforms or moves under the load of the moving liquid, and the deformation or movement of the solid in turn reverses the movement of the liquid, thereby changing the action on the solid surface Load. The fluid-solid coupling equation is composed of a fluid domain and a solid domain to jointly solve the fluid-solid coupling problem [6].

The discrete wave equation of the interface loss is as follows:

$$[\mathbf{M_P}]\{\ddot{\mathbf{P}}\}+[\mathbf{C_P}]\{\dot{\mathbf{P}}\}+[\mathbf{K_P}]\{\mathbf{P}\}+\rho[\mathbf{R}]^T\{\ddot{\mathbf{u}}\}=0 \tag{1}$$

where $[\mathbf{M_P}]$ is the fluid mass matrix; $[\mathbf{C_P}]$ is the fluid damping matrix; $[\mathbf{K_P}]$ is the fluid stiffness matrix; $\rho[\mathbf{R}]^T$ is the coupling mass matrix; ρ is the density of the water body; $\{\mathbf{P}\}$ is the hydrodynamic pressure vector; $\{\ddot{\mathbf{u}}\}$ is the nodal acceleration vector.

The discrete dynamic equation of the structure is as follows:

$$[\mathbf{M}]\{\ddot{\mathbf{u}}\}+[\mathbf{C}]\{\dot{\mathbf{u}}\}+[\mathbf{K}]\{\mathbf{u}\}-[\mathbf{R}][\mathbf{P}]=\{\mathbf{F}\} \tag{2}$$

where $[\mathbf{M}]$ is the structural mass matrix; $[\mathbf{C}]$ is the structural damping matrix; $[\mathbf{K}]$ is the structural stiffness matrix; $\{\mathbf{u}\}$ is the nodal displacement vector; $\{\dot{\mathbf{u}}\}$ is the nodal velocity vector; $[\mathbf{R}]$ is the coupling matrix, representing the effective surface area associated with the nodes on the fluid-structure interface, and it considers the composition The normal vector direction of each pair of overlapping fluid and structural element faces on the contact surface; $\{\mathbf{F}\}$ is the structural load vector.

By combining the discrete equations of formula (1) and formula (2), the following equation can be obtained:

$$\begin{bmatrix}[\mathbf{M}] & [\mathbf{0}]\\ [\mathbf{M}^{fs}] & [\mathbf{M}_P]\end{bmatrix}\begin{Bmatrix}\{\ddot{\mathbf{u}}\}\\ \{\ddot{\mathbf{P}}\}\end{Bmatrix}+\begin{bmatrix}[\mathbf{C}] & [\mathbf{0}]\\ [\mathbf{0}] & [\mathbf{C}_P]\end{bmatrix}\begin{Bmatrix}\{\dot{\mathbf{u}}\}\\ \{\dot{\mathbf{P}}\}\end{Bmatrix}+\begin{bmatrix}[\mathbf{K}] & [\mathbf{K}^{fs}]\\ [\mathbf{0}] & [\mathbf{K}_P]\end{bmatrix}\begin{Bmatrix}\{\mathbf{u}\}\\ \{\mathbf{P}\}\end{Bmatrix}=\begin{Bmatrix}\{\mathbf{F}\}\\ \{\mathbf{0}\}\end{Bmatrix} \tag{3}$$

$$[\mathbf{M}^{fs}]=\rho[\mathbf{R}]^T;[\mathbf{K}^{fs}]=-[\mathbf{R}] \tag{4}$$

When the structure vibrates, ignoring the influence of structural damping and load, the following equation can be obtained from expression (3):

$$\begin{bmatrix}[\mathbf{M}] & [\mathbf{0}]\\ [\mathbf{M}^{fs}] & [\mathbf{M}_P]\end{bmatrix}\begin{Bmatrix}\{\ddot{\mathbf{u}}\}\\ \{\ddot{\mathbf{P}}\}\end{Bmatrix}+\begin{bmatrix}[\mathbf{K}] & [\mathbf{K}^{fs}]\\ [\mathbf{0}] & [\mathbf{K}_P]\end{bmatrix}\begin{Bmatrix}\{\mathbf{u}\}\\ \{\mathbf{P}\}\end{Bmatrix}=\begin{Bmatrix}\{\mathbf{0}\}\\ \{\mathbf{0}\}\end{Bmatrix} \tag{5}$$

Solving equation (5) can get the frequency and mode shape of structure and fluid coupling vibration.

3. Method verification

For the hydrodynamic pressure simulation of the double-sided water-retaining thin plate, the traditional simulation method is to simulate the water body with additional mass. Later scholars use the potential fluid method to simulate the hydrodynamic pressure, but the simulation of the thin plate uses solid elements. This paper proposes to use shell elements to simulate thin plates. First, verify the correctness of shell element simulations by comparing the simulation results of shell elements and solid elements.

The corresponding finite element model is established according to the analysis model of the double-sided water-retaining thin plate in Figure 1, and the solid element and the shell element are used to simulate the thin plate respectively to verify the correctness of the shell element simulation. The numerical simulation in this paper uses the fluid-structure coupling method in ANSYS, the thin plate is simulated by SHELL63 and SOLID45 elements, and the water body is simulated by FLUID30. The KEYOPT(2) of the water element in contact with the thin plate is set to 0, the contact element has four degrees of freedom, including three displacement degrees of freedom and one pressure degree of freedom, and the KEYOPT(2) of the water element not in contact with the thin plate is set to 1. , The contact element has only one pressure degree of freedom. The height H of the model is 10m, the thickness T is 0.1m, the width B is 10m, h1 is 10m, h2 is 5m, and the length of the water body is 40m.

When using solid elements to simulate a thin plate, the meshes of the solid element group and the water element group are fitted at the coupling boundary, that is, the contact position of the solid element and the water element is the common node, and then the fluid-structure coupling boundary is applied to the nodes at the boundaries on both sides. When the shell element is used to simulate a thin plate, the meshes of the shell element group and the water element group do not fit at the coupling boundary, that is, the contact position of the shell element and the water element is not the same node, but the node of the fluid-structure coupling boundary needs to be the same. One correspondence, that is, the position coincides, and then the translational degrees of freedom of the nodes on the fluid-structure coupling boundary are coupled, and finally the nodes at the water boundary on both sides of the shell impose the fluid-structure coupling boundary.

For the simulated infinite absorbing boundary condition, change the element properties of the fluid element boundary area to make MU=1 [3]. The bottom of the thin plate is fixed, and the pressure on the free surface of the water body is 0. The material properties of various parts are shown in Table 1.

Table 1. Material properties of different parts

Part type	ρ ($Kg \cdot m^{-3}$)	E (GPa)	μ	ν ($m \cdot s^{-1}$)
Sheet	7830	210	0.274	
Water	1000			1440

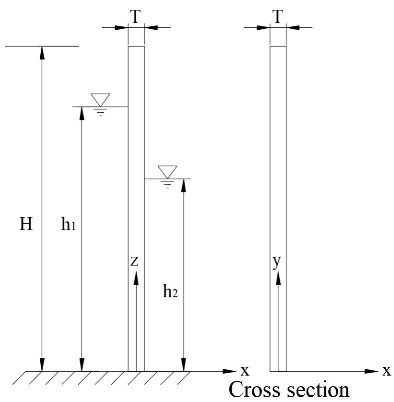

Figure 1. Analysis model of double-sided water retaining sheet

The finite element model of the double-sided water retaining sheet is shown in Figure 2.

The modal analysis is performed on these two different models, and the asymmetric modal extraction method is adopted. The frequency results of the modal analysis are shown in Figure 3. It can be seen from Fig. 3 that the fundamental frequency of model I (shell element simulation thin plate) is 0.427 Hz, and the fundamental frequency of model I (solid element simulation thin plate) is 0.43 Hz. The relative error between the two is 0.64%. The relative errors of the sixth-order frequencies are all less than 10%, indicating that the results of the shell element simulation and the solid element simulation are still better, which also shows the correctness of this method.

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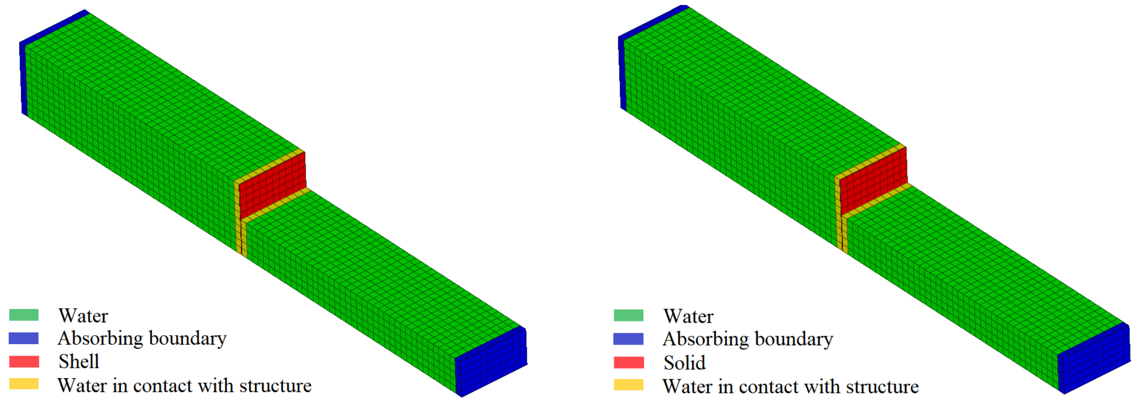

(a) Model 1 (b) Model 2

Figure 2. Finite element model of double-sided water retaining sheet

In order to compare the dynamic response under different water level conditions, this paper analyzes four different working conditions. See Table 2 for the water levels of various working conditions.

Table 2. Upstream and downstream water levels for different working conditions

Condition	Upstream water level(m)	Downstream water level(m)
1	0	0
2	10	0
3	10	5
4	10	10

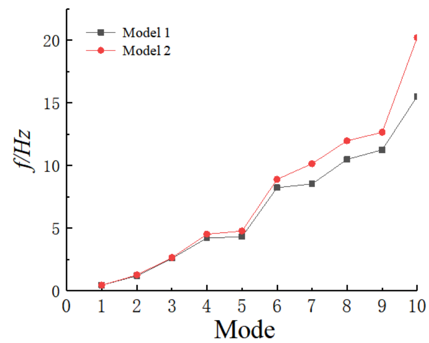

Figure 3. Comparison of natural frequency of Model 1 and Model 2

This paper conducts vibration analysis and seismic time history analysis on four different water levels, and compares the vibration and dynamic characteristics of thin plates under different working conditions. Figure 4 shows the seismic acceleration time history curve along the river.

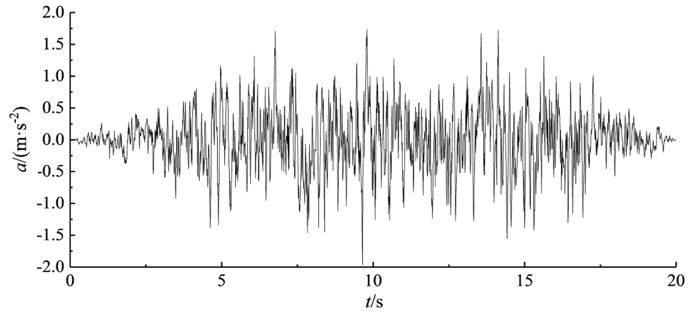

Figure 4. Time-history curve of seismic acceleration along the river

4. Calculation results and analysis

4.1. Modal results and analysis

Through the modal calculations under four working conditions, the first five modes of each working condition are extracted for analysis. The modal results of various working conditions are shown in Table 3.

Table 3. Modal results of different working conditions

Order	Condition 1 (Hz)	Condition 2 (Hz)	Condition 3 (Hz)	Condition 4 (Hz)
1	0.861	0.431	0.427	0.325
2	2.139	1.205	1.182	0.928
3	5.309	2.776	2.573	2.174
4	6.759	4.325	4.198	3.431

It can be seen from Table 3 that there are obvious differences in the frequency of vibration of the thin plate under different working conditions. Comparing working condition 1 and working conditions 2-4, it is not difficult to find that the vibration frequency of the thin plate dry mode is higher than that of the wet mode; comparing working condition 2 and working conditions 3-4, it can be obtained that the thin plate with water on one side is better than double The vibration frequency with water on the side is large; comparing Working Condition 3 and Working Condition 4, the vibration frequency of low water level is larger than that of high water level. The working conditions 1 to 4 fully illustrate that in the presence of water, the vibration frequency of the thin plate is reduced.

4.2. Analysis of hydrodynamic pressure

By taking the hydrodynamic pressure of a row of nodes (y=5m) in the middle of the thin plate, and taking the hydrodynamic pressure amplitude of each node separately, draw the line graph of hydrodynamic pressure amplitude and height under different working conditions, as shown in Figure 5.

It can be seen from Figure 5 that under different water level conditions, the dynamic water pressure amplitude of the thin plate will be quite different. Comparing working condition 2 and working condition 3, it can be seen that the amplitude of hydrodynamic pressure of the two working conditions is almost the same in the range of height 5-10m, and the amplitude of hydrodynamic pressure increases in the range of 0-5m, indicating The hydrodynamic pressure on both sides is superimposed. By comparing Working Condition 2 and Working Condition 4, the amplitude of the hydrodynamic pressure with water on both sides is larger than the amplitude of hydrodynamic pressure with water on only one side, indicating that the hydrodynamic pressure with water on both sides is superimposed.

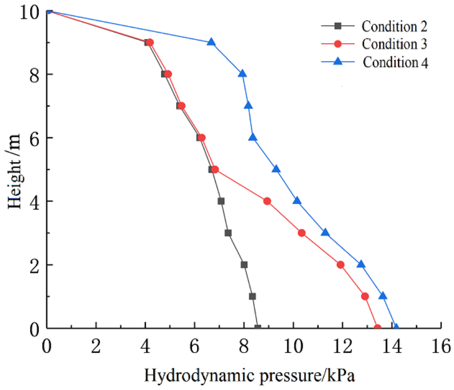

Figure 5. The amplitude curve of hydrodynamic pressure at different heights

5. In conclusion

This paper compares and analyzes the influence of the water level of four different working conditions on the natural frequency and dynamic response of the thin plate. The results of the modal analysis show that considering the effect of water will reduce the natural frequency of the structure. The natural frequency of the structure with water on both sides is smaller than that with water on one side, and the water level will affect the natural frequency of the structure. The higher the water level, the lower the natural frequency of the structure. The results of the dynamic time history indicate that considering the effect of water bodies will strengthen the dynamic response of the structure. The dynamic response with water on both sides is greater than that with water on one side. The higher the water level, the greater the dynamic response of the structure. Therefore, in the dynamic analysis of water retaining structure, the water bodies on both sides should be fully considered.

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