Seismic Response Analysis of the Underwater High-rise Independent Intake Tower

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ABSTRACT :
In this study, the seismic response of the high-rise intake tower in the spillway tunnel of a hydropower station is analyzed. The intake tower is in underwater and independent. The commercial finite element software ANSYS is used to develop a 3D dynamic finite element analysis model of structure-water-foundation. A simulation method of hydrodynamic pressure of the underwater intake tower is studied. The dynamic characteristic of the underwater intake tower is analyzed. Time history analysis method is used to calculate the seismic response of the intake tower structure under the horizontal earthquake. The most unfavorable position of the intake tower for earthquake occurrence is given and the corresponding shock absorption measures is provided. The results provide science reference for the engineering design.

KEYWORDS:
underwater ;intake tower ; high-rise ; seismic response ; time history analysis

1.Introduction

The high-rise tower structure is often used in the intake of the power tunnel or spillway tunnel in diversion-type hydropower station. Because it has higher height, less stiffness and complex structure, seismic safety is one of the main control factors taken into consideration in intake tower structure design. The intake tower in the spillway tunnel of Weiyuanjiang hydropower station is 85m high with its left side, right side and backside connected with the mountain by backfill concrete. The upper part of the tower is independent and more than 40 meters high. It is a high-rise independent underwater building as most of the internal and external part of the tower is underwater during the normal runtime. The section size of the tower is 15m×10.3m and the thickness of its concrete wall is 2.2m-2.9m. Its foundation is composed of weak slightly weathered sandstone and mudstone. The mechanism of dynamic interaction of concrete structure, water and rock mass is very complex. The seismic design intensity of the engineering is 7 degree. Therefore, it is very important to study on a reasonable dynamic calculation model and calculation method to analyze the tower. In this paper, according to the underwater high-rise independent intake tower in the spillway tunnel of Weiyuanjiang hydropower station, a 3D dynamic finite element analysis model of structure-water-foundation is developed. A simulation method of hydrodynamic pressure of the underwater intake tower is studied. Time history analysis method is used to calculate the dynamic characteristic and seismic response of the intake tower structure. The results provide science reference for structural seismic design.

2. Dynamic time history simulation

2.1 Dynamic analysis method

The finite element equation of structure-water-foundation system under earthquake action [1] is:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=[M]\{G(t)\} \qquad (2.1)$$

Where $[M]$ is system mass matrix, $[C]$ is system damp matrix, $[K]$ is system rigidity matrix, $\{G(t)\}$ is ground acceleration matrix, and $\{U\},\{\dot{U}\},\{\ddot{U}\}$ are respectively displacement, velocity and acceleration matrix of nodes.

The equation above adopts Newmark time—integrated method to calculate on disperse point. Full system matrices method (full method) is used to calculate structure response in time history response analysis. This is a method with simplicity and high precision. But it will ignore invariable damping ratio and mode damping ratio. Therefore we use Rayleigh damping here to express total system damping matrices. that is

$$[C]=\alpha[M]+\beta[K] \tag{2.2}$$

Where α、β can be calculated according to following formula [3]:

$$\alpha=\frac{2\omega_i\omega_j(\zeta_i\omega_j-\zeta_j\omega_i)}{(\omega_j^2-\omega_i^2)} \qquad \beta=\frac{2(\zeta_j\omega_j-\zeta_i\omega_i)}{(\omega_j^2-\omega_i^2)}$$

Where ζ_i,ζ_j are the damping ratio of the *i*th and *j*th mode; ω_i,ω_j are the frequency of the *i*th and *j*th mode.

2.2 Hydrodynamic pressure simulation

The intake tower of Weiyuanjiang hydropower station will be underwater during the normal runtime, so seismic calculation should reckon in seismic hydrodynamic pressure. The inside area of the tower is full filled with water. The inside water area of the tower is regarded as the finite water area and has the internal water pressure on the tower. And the outside water area of the tower is regarded as the infinite water area and has the external water pressure on the tower. In order to consider influence of hydrodynamic pressure of both finite water area and infinite water area, we study rigid rectangular water area as shown in Fig.1 by using a solution based on the assumption that water is incompressible. Let a be the length of the rigid area while h is the depth of water per unit width. Then according to hydrodynamics theory, considering the sidewall boundary condition, the analytical solution of hydrodynamic pressure on every sidewall can be obtained by derivation as follow:

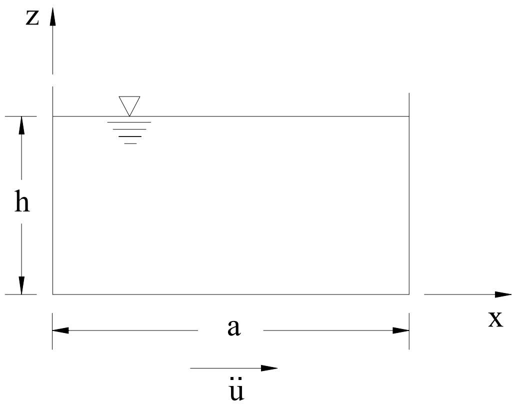


Figure1 Horizontal vibration in rectangular water area

$$p^*(0,z)=-p^*(a,z)=\frac{8}{\pi^2}\rho h\ddot{u}_0\left(\sum_{n=1,3,\cdots}^{\infty}\frac{1}{n^2}(-1)^{\frac{n-1}{2}}th\frac{n\pi a}{4h}\cos\frac{n\pi z}{2h}\right) \tag{2.3}$$

Where $\ddot{u}_0$ is horizontal acceleration amplitude, ω is simple harmonic vibration frequency, $p^*(x,z)$ is hydrodynamic pressure of rigid water area, ρ is water density.

Using formula (2.3), we can obtain the added mass of hydrodynamic pressure. According to the principle that hydrodynamic pressure on sidewall is equal to added inertia force, we can get formula to solve added mass of hydrodynamic pressure as follow:

$$m_x(z)=\frac{8}{\pi^2}\rho h(\sum_{n=1,3,\cdots}^{\infty}\frac{1}{n^2}(-1)^{\frac{n-1}{2}}th\frac{n\pi a}{4h}\cos\frac{n\pi z}{2h}) \tag{2.4}$$

Where $m_x(z)$ is the added mass per unit area on sidewall; h is the depth of water retaining sidewall . Multiplying m_x by the area around every node on the water retaining face of the sidewall, we can then sum up them to get the added mass of hydrodynamic pressure of the node. The whole mass matrix of structure-water can be obtained by adding the mass to structure mass matrix. From formula (2.3) -(2.4) we can see that when $\frac{a}{h}>3$, then $th\frac{n\pi a}{4h}\approx 1$ which accords with Westergard solution about infinite water area, so both finite and infinite area can be calculated by this solution. It can conveniently be used in finite element dynamic analysis.

2.3 Artificial seismic wave generation

When using the time-history method to analyze the seismic effects , a seismic acceleration time-history curve has to be input. It's also very important to choose an appropriate seismic wave to ensure the reliability of the results in dynamic analyses.

In this paper, according to the seismic design response spectrum[4] based on "Code for seismic design of hydraulic structures", we use artificial simulation method to generate seismic wave, with the purpose of analyzing the intake tower seismic response during normal runtime period. Firstly, the base spectrum can be calculated with the typical value of horizontal design seismic acceleration (α=0.15g) and characteristic period (T=0.3s). Then the spectrum is used with the 20s duration and 10 times iteration by program to generate an acceleration time history curve (shown in Fig.2).

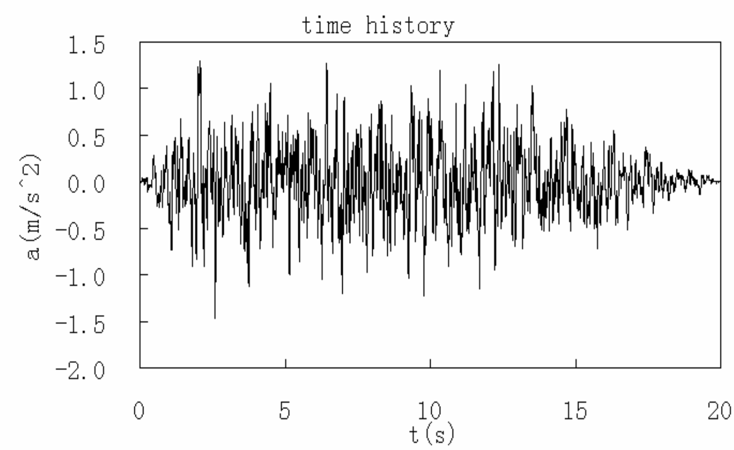


Figure 2 Artificial seismic wave

3. Calculation model and parameter

3.1 Calculation model

To built the three-dimensional finite element model of intake tower structure, pile foundation and ground foundation, according to topographic condition, ground foundation simulation range is selected with 30,30,45,45 meters on the upstream side, the left side, the downstream side and the right side respectively away from the tower and 45 meters depth away from ground foundation. The complex structures including the trumpet intake of the tower, inside gate slot, the breast wall and so on is simulated accurately. And then the model is meshed according to different materials by using mapping mesh to ensure the precision of calculation. The isoparametric hexahedral element type is used to simulate the concrete and the foundation, the beam element type is used to simulate the piles, and the space link element type is used to simulate the anchor. The Coordinate System is selected as that: X axis is along the current, Y axis is upward vertically, Z axis is vertical to the current and points to right, and the coordinate origin is located at the symmetry plane of the intake tower base surface. The whole three-dimensional finite element model of intake tower and its foundation has 27427 nodes and 23303 elements in which there are 23005 block elements, 118 pile elements and 180 anchor elements. The 3D finite element model is shown in Fig.3～Fig.4. Constraint conditions are: normal chain constraint around the foundation, fixed constraint on the bottom surface of foundation. Both outside and inside hydrodynamic pressure of the intake tower are simulated by the method discussed in chapter 2.2.

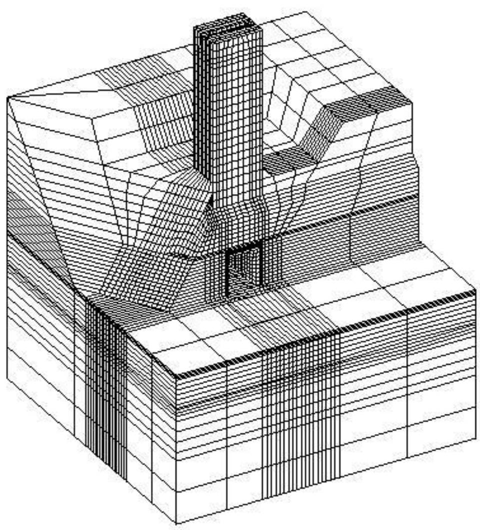


Figure 3 3D finite element mesh of intake tower and foundation

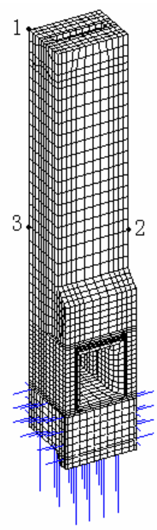


Figure 4 3D finite element mesh of intake tower and key points

3.2 Model material parameter

The intake tower is made up of three kinds of structure concrete. C25 is used above elevation of 860m which elastic modulus E =2.8×10^4MPa, C30 is used Below height 860m which elastic modulus E=3.0×10^4MPa，the inside of the foundation is partly filled with C20 which elastic modulus E=2.55×10^4MPa. The backfill concrete is C15 which elastic modulus E=2.2×10^4MPa. For above kinds of concrete, density ρ=2450kg/m^3，Poission's ratio μ=0.167. For reinforced concrete pile, equivalent elastic modulus E=4.71×10^4MPa，equivalent density ρ=3388.66kg/m^3，Poission's ratio μ=0.3. For anchor, elastic modulus E=2.1×10^5MPa，density ρ=7850kg/m^3，Poission's ratio μ=0.3. According to the standard[4], when calculate seismic intensity of concrete hydraulic structure, concrete dynamic elastic modulus standard value can be 30% more than the static value. In this paper, the intake tower body concrete elastic modulus was added to 30% compare with its static value.

Upper foundation is composed of weak weathered rock, its elastic modulus E=0.5×10^4MPa，density ρ=2500kg/m3，Poission's ratio μ=0.265；Lower foundation is composed of slightly weathered and fresh rock，its elastic modulus E=0.75×10^4MPa，density ρ=2600kg/m^3，Poission's ratio μ=0.24.

4. Analysis of tower dynamic characteristics and seismic response

4.1 Dynamic characteristics

Analyzing and recognizing dynamic characteristic of structure is the base of analyzing its dynamic response. According to the three-dimensional finite element model established in chapter 2.1, we can obtain main natural frequency and its respectively mode of the structure, that is shown in Table 1.The result shows that the fundamental frequency of the intake tower structure is 1.278 Hz, period is 0.783 s; the second frequency is 3.576 Hz, period is 0.783 s. The first mode mainly vibrates along the current, the second mode mainly vibrates vertical to the current, the third mode demonstrates torsion deformation, and the fourth mode has the trends of bend and torsion deformation. The first mode contributes the most in seismic response.

Table 1 The first 10 orders modal natural frequency and period

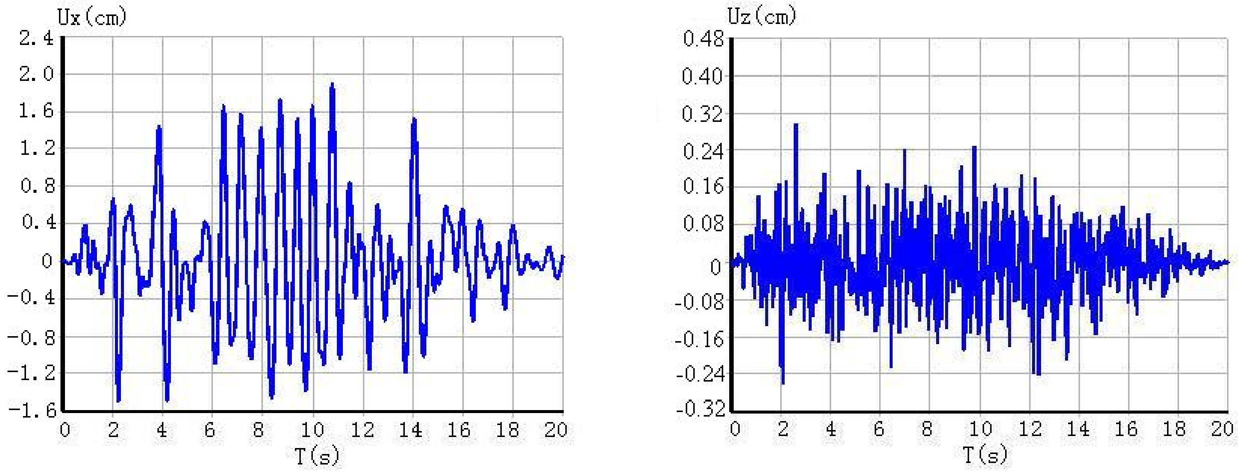
Mode orders	1	2	3	4	5	6	7	8	9	10
Frequency(Hz)	1.278	3.576	4.709	4.795	5.892	7.369	8.205	8.698	8.710	9.515
Period(s)	0.783	0.280	0.212	0.209	0.170	0.136	0.122	0.115	0.115	0.105

4.2 Seismic response analysis

This paper is mainly focused on the analysis of the seismic response of the intake tower during the normal runtime. The seismic wave generated in chapter 2.3 is used to analyze the seismic response of the 3D finite element model above, the main conclusions discussed as follow:

(1)Structure dynamic displacement

Under the horizontal earthquake action along the current, the main dynamic displacement of the intake tower is along the current, and the maximum value is 1.92cm occurring about 10.6s after the earthquake begins on the left side of the tower top. The maximum value of vertical displacement of the tower top is 0.23cm, the value vertical to the current is 0.032cm, and neither of them has controlling effects. The maximum value of the horizontal dynamic displacement of the tower body that contacts with the top of backfill concrete is 0.12cm while the vertical one is 0.11cm. The maximum value of the horizontal dynamic displacement of foundation corner point and the vertical one are much smaller and are not controlling factors. Under the earthquake action vertical to the current, the main dynamic displacement of the intake tower is vertical to the current too, and the maximum value is 0.30cm occurring about 4.2s after the earthquake begins on the left side of the tower top. Similar to the one along the current., the values of the dynamic displacement on tower top either along or vertical to the current, the values of the horizontal dynamic displacement of tower body that contacts with the top of backfill concrete and the values of foundation bottom are all small and have no controlling effects. The displacement time history curves of key point 1 (location of key point can be seen in Fig.4) are shown in Fig.5, Fig.(a）shows displacement along the current under the earthquake along the current. Fig.(b）shows displacement vertical to the current under the earthquake vertical to the current. The results show that, the main vibration occurs on the independent tower body above the backfill concrete, and the dynamic displacement along the current is much larger than the one vertical to the current.



（a）displacement along the current under the earthquake action along the main current

（b）displacement vertical to the current under the earthquake action vertical to the current

Figure 5 Displacement of key point 1 time history curve under the horizontal earthquake action

(2) Structure dynamic stress

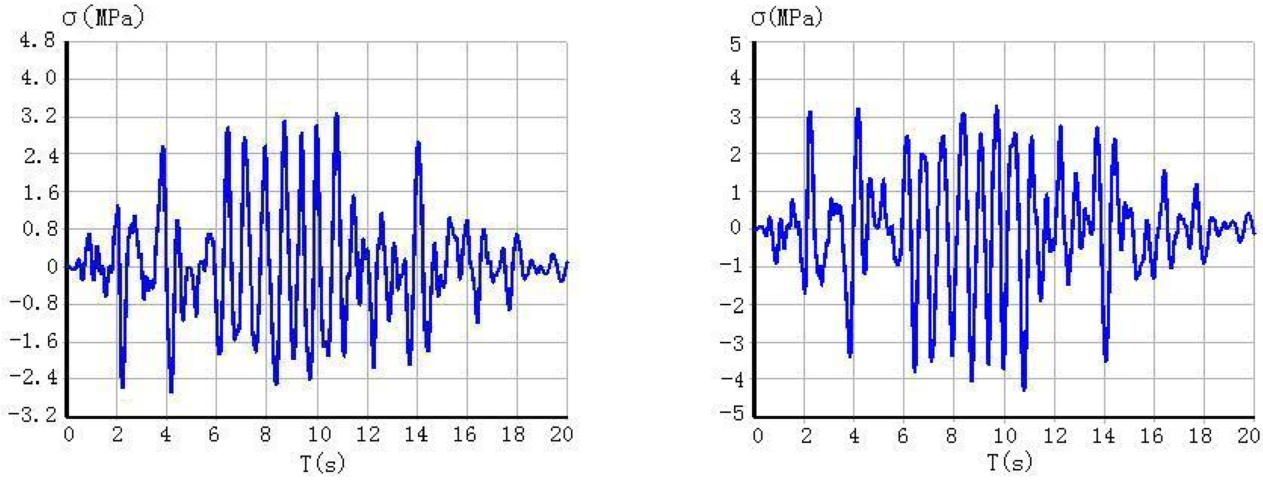
Under the horizontal earthquake action along the current, the maximum dynamic stress is mainly vertical, occurring on tower body that near the part contacted with the top of backfill concrete where there are stress concentration. The maximum value of vertical tension stress of downstream key point 3 is 3.32MPa, occurring about 9.8s after earthquake begins, and the maximum value of compressive stress is 4.34MPa, occurring about 10.8s after earthquake begins. The maximum value of tension stress of upstream key point 2 is 3.26MPa, occurring about 10.7s after earthquake begins, and the maximum value of compressive stress is 2.7MPa, occurring about 4.1s after earthquake begins. The stresses of the other parts of the structure are all small. The vertical stress time history curves of two key points on the body contacted with the top of backfill concrete under earthquake action along the current (location of key point can be seen in Fig.4) are shown in Fig.6.

Under the horizontal earthquake action vertical to the current, the maximum dynamic stress also occurs on tower body that near the part contacted with the top of backfill concrete where there are stress concentration. The maximum value of tension stress of downstream key point 3 is 0.98MPa, occurring about 2.3s after earthquake begins, and the maximum value of compressive stress is 0.83MPa, occurring about 2.1s after earthquake begins. The maximum value of tension stress of upstream key point 2 is 0.59MPa, occurring about 2.1s after earthquake begins, and the maximum value of compressive stress is 0.66MPa, occurring about 2.3s after earthquake begins. The stresses of the other parts of the structure are all small. The vertical stress time curves of two key points on body contacted with the top of backfill concrete under earthquake action vertical to the current (location of key point can be seen in Fig.4)are shown in Fig.7.

The results show that, the dynamic stress under earthquake action along the current is much larger than the one under earthquake action vertical to the current. Therefore, earthquake along the current has much more adverse effects than the one vertical to the current on the structure of intake tower.

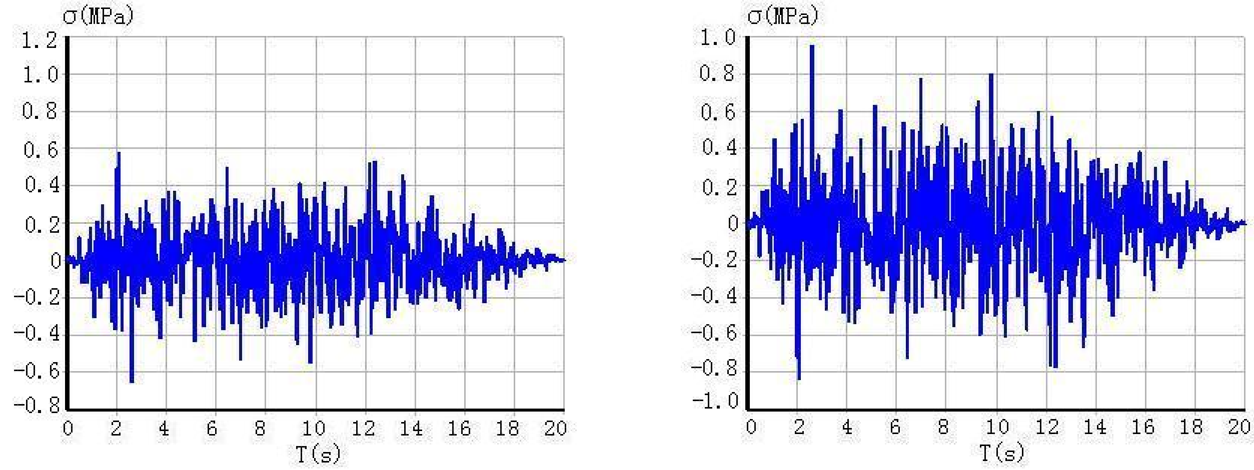
5．Conclusions

In this paper, time-history analysis method is used to analyze the dynamic characteristic and seismic response of underwater high-rise independent intake tower of the spillway tunnel of Weiyuanjiang hydropower station. The time history curves of the stress and displacement of the intake tower subjected to horizontal earthquake during normal runtime are obtained. The seismic response of the high-rise intake tower under earthquake action along the current is more significant, the dynamic stress and displacement are much larger, and the main vibration occurs on the independent tower body above the backfill concrete. The maximum dynamic stress is mainly vertical stress, occurring on tower body that near the part contacted with the top of backfill concrete, where there is stress concentration that may result in local concrete cracking. It is suggested that: 1) Lay out seismic reinforcement on tower body that near the part contacted with the top of backfill concrete where the value of dynamic stress is large; 2) Because of the great stiffness of backfill concrete contacted with tower body and the rigid contact, it is easy to generate stress concentration. It is also suggested to add triangle foreland on tower body contacted with backfill concrete, so as to reduce contact rigidity, release stress concentration, lesson dynamic stress.



（a）upstream key point 2 （b）downstream key point 3

Figure 6 Key points on body contacted with the top of backfill concrete vertical stress under earthquake action along the current



（a）upstream key point 2 （b）downstream key point 3

Figure 7 Key points on body contacted with the top of backfill concrete vertical stress under earthquake action vertical to the current

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