Comparative analysis of dynamic characteristics of Intake Towers based on Pseudo-Static and Response Spectrum Method

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Comparative analysis of dynamic characteristics of Intake Towers based on Pseudo-Static and Response Spectrum Method

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Abstract. This study analyses the intake tower of a pumped storage power station in a dynamic way. The pseudo-static and response spectrum methods are used to obtain the stress–displacement distribution of the intake tower structure under normal water storage conditions. The extreme values of stress and displacement in the X, Y and Z directions and the differences of their locations are comparatively analysed. The path of the maximum principal stress of the protruding part is finally obtained. Results show that under seismic conditions, the pseudo-static and response spectrum methods can reflect changes in stress. The pseudo-static method is relatively safe, but using the response spectrum method out of reach of an anti-seismic location is more reasonable. The research results can serve as a reference for the structure design of intake towers.

1. Introduction

Intake towers [1-3] are generally set in the influent and effluent systems of engineering projects. The anti-seismic safety and stability of intake towers directly lead to the normal operation of power stations. The existing research shows that the comparative analysis of the response spectrum method and the pseudo-static method in the dynamic analysis of intake towers is not sufficiently specific. The response spectrum method is preferred for static and dynamic calculation. Researchers found pseudo-static method [4] is theoretically simple and reliable with a long application time and strong practicality. The response spectrum method reflect the weak parts of structures and is advantageous for the reinforcement of anti-seismic structures. The current work uses the pseudo-static and response spectrum methods to calculate the dynamics of an intake tower. The characteristics of the two methods are explored, and their applicability to the anti-seismic design of intake towers is analysed.

2. Project overview

2.1. Basic data

In a pumped storage electric station, the normal water storage capacity of the lower reservoir is 1761 m, the total installed capacity is 1200 MW (4×300 MW), the main dam is a concrete face rockfill dam, and the maximum dam height (at the dam axis) is 87 m. The water intake tower is a first-class (1) project, and the main building grades for water retention, water discharge and water diversion power device of the upper and lower reservoirs are Class I.

2.2. Range and model of calculation
This study investigates the distribution of stress displacement of the intake tower structure at a normal water storage level (horizontal seismic acceleration is 0.394 g) during an earthquake. The loads for the following are calculated accordingly: weight of the intake tower, hydrostatic pressure, hydrodynamic pressure, uplift pressure, wave pressure and seismic force outside and inside the tower. The intake tower, tower height (upstream and downstream), left and right banks and depth are taken as research objects. For the intake tower structure, the model mesh of the tower body model is a hexahedral solid. In analysing the main force of the intake tower, the beam unit is adopted to simulate the top bent structure of the intake tower. The shell element is used to simulate the hoist layer and truss top layer. The calculation model of the finite element meshing is shown in figure 1and figure 2.

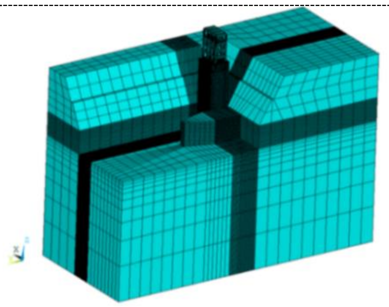

Figure 1. Finite element meshing of whole model

Figure 2. Finite element meshing of intake tower model

2.3. Earthquake overview
This study adopts the peak ground acceleration of the horizontal seismic bedrock with an exceedance probability of 2% within 100 years of the base period. The lower reservoir is 386.2 m/s^2. The characteristic period is 0.55 s. The peak acceleration in the vertical direction is two-thirds that in the horizontal direction. According to the ‘Code for Anti-Seismic Design of Hydraulic Structures for Hydropower Projects’ (NB 35047-2015) [5], the project include horizontal and vertical earthquakes.

3. Dynamic analysis

3.1. Pseudo-static method
When the pseudo-static method is used to calculate the horizontal seismic inertial force F_i of the intake tower acting on the mass point *i* along the height direction, the tower body is divided into two parts for calculation (Figure 3). The row frame at the top of the tower is divided into two parts 16.00 m away from the top of the tower (Figure 4). The seismic inertia forces of the block for tower bodies①, ②, ③ and ④ are calculated.

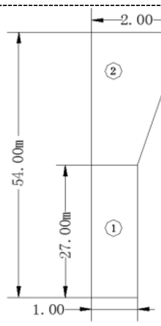

Figure 3. Dynamic distribution coefficient of seismic inertia force of tower body

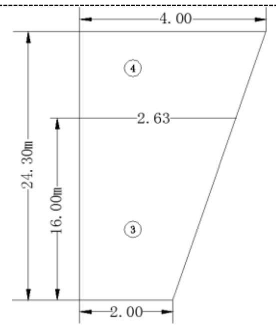

Figure 4. Dynamic distribution coefficient of seismic inertia force of the top bent part of the tower body

The calculation is as follows:

$$F_i = \alpha_h \xi G_{Ei} \alpha_i / g \quad (1)$$

α_h is the representative value of seismic acceleration at the horizontal direction, α_h =0.349 g, ξ =0.25 is the reduction factor of the seismic effect; if ξ =0.25, then G_{Ei} is the standard value of gravity acting on particle *i, KN*; α_i is the dynamic distribution coefficient of point *i*. The vertical seismic inertia force is calculated according to equation (1), where the vertical seismic acceleration is represented by the value α_v substituted for α_h and the peak acceleration in the vertical direction is two-thirds that in the horizontal direction. The total seismic action effect is multiplied by a coupling coefficient of 0.5 and superposes the horizontal seismic action effect.

When calculating the representative value of the combined force at the unit height of the water pressure of the tower ground motion at water depth h, the following equation (2) shall be followed:

$$F_T(h) = \mathrm{a}_h \xi \rho_w \psi(h) \eta_w A(\frac{\mathrm{a}}{2H_0})^{-0.2} \quad (2)$$

where $F_T(h)$ as the representative value of the joint force of the hydrodynamic pressure at the unit height of the water depth *h*; $\psi(h)$ as the distribution coefficient of earthquake hydrodynamic pressure at depth h, $\psi(h)$ is 0.72 in the tower ; ρ_w as the standard value of the water mass density, that is, 1000 kg/m^3; η_w is the shape factor whose value inside the tower and outside the round tower is 1.0 and whose value outside the rectangular tower is based on [5]; A is the area of the tower body along the average elevation cross section and the enveloped area of the water body; a is the average value of the maximum width of the water-facing surface along the vertical seismic action of the tower body; α_h and ξ have the same meanings as those in equation (1).

As the distribution coefficient of the shaking water pressure outside the tower varies with water depth *h*, the groundwater pressure function is written separately along the elevation section, and the equivalent surface force is applied to the tower surface.

3.2. Mode-decomposition response spectrum method

In the analysis of the hydrodynamic pressure of the intake tower, the influence of the compressibility of the water body can be ignored. Therefore, the hydrodynamic pressure only reflects the inertia effect and can be treated as additional mass. According to the [5],

$$m_w(h) = \psi_m(h) \rho_w \eta_w A(\frac{a}{2H_0})^{-0.2} \quad (3)$$

Where $m_w(h)$ is the representative value of the dynamic water pressure at the unit height of water depth *h*; $\psi_m(h)$ is the distribution coefficient of the additional mass; the dynamic water pressure inside the tower is 0.72 and that outside the tower is based on [5]; H_0 is the water depth in front of the tower. In the formula, the meanings of ρ_w, η_w, A and a are the same as those in equation (2).

When using the mode-decomposition response spectrum method, the maximum response spectrum β_{max} =2.5, and the characteristic period is 0.55 s. Figure 5 shows the designed response spectrum used for the anti-seismic calculation of the intake tower structure of the lower reservoir of the pumped storage power station project.

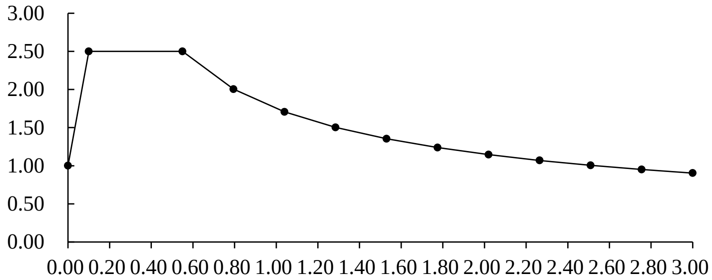

Figure 5. Designed response spectrum used in the calculation

4. Result analysis

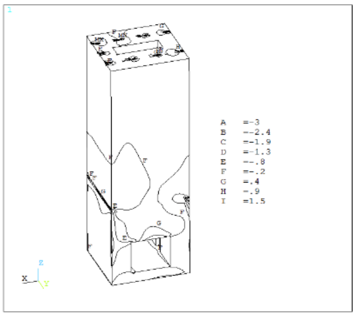

Figure 6. Diagram of stress cloud of the tower body (MPa) in the X direction

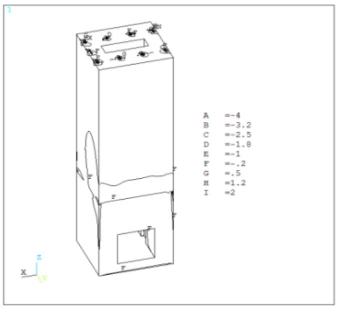

Figure 7. Diagram of stress cloud of the tower body (MPa) in the Y direction

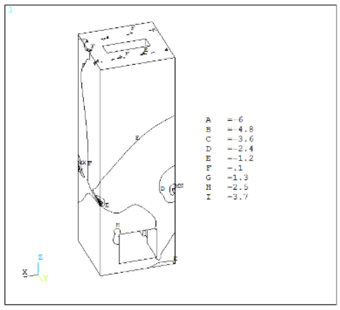

Figure 8. Diagram of stress cloud of the tower body (MPa) in the Z direction

The calculation results obtained through the pseudo-static method show the following. The structural stress diagram of the intake tower structure shows that due to the stress concentration, the external side of the tower body has a large online stress with the slope of the surrounding rock mass, and the stresses in all three directions are small. The maximum tensile stress at the top surface of the intake tower reaches 1.5 MPa (Figure 6). The maximum tensile stress in the Y direction reaches 2.6 MPa (Figure 7). The maximum tensile stress in the Z direction reaches 4.0 MPa (Figure 8).

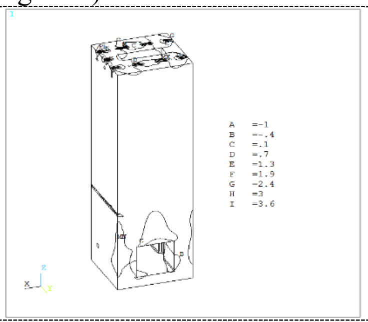

Figure 9. Diagram of stress cloud of the tower body (MPa) in the X direction

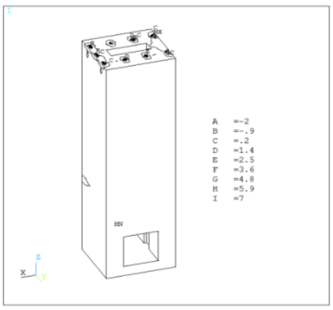

Figure 10. Diagram of stress cloud of the tower body (MPa) in the Y direction

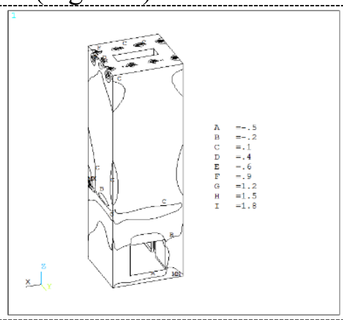

Figure 11. Diagram of stress cloud of the tower body (MPa) in the Z direction

The calculation result is obtained by the vibration mode decomposition response spectrum method. The overall structural stress diagram of the intake tower shows that due to stress concentration, the outer side of the tower intersects with the surrounding rock slope. Moreover, the online stress is large, and the stresses in all three directions are small. The maximum tensile stress on the top surface of the intake tower in the X direction reaches 5.2 MPa (Figure 9). The maximum tensile stress in the Y direction reaches 7.2 MPa (Figure 10). The tensile stress value in the Z direction is small, and the

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maximum value is 2.0 MPa. A certain concentration of stress is observed. The maximum value of the tensile stress appearing on the upstream side of the intersection line between
the outer side of the tower and the right side of the rock mass has a value of 2.0 MPa (Figure 11).

The structural displacement shows that the calculation result obtained by the pseudo-static method is similar to that obtained by the response spectrum method and that the displacement extremes appear at the same position. Both methods can be used in the calculation of displacement. For the stress calculation, the calculation result obtained by the pseudo-static method is greater than that obtained by the response spectrum method. The acceleration of the pseudo-static method is always the peak acceleration of an earthquake in the case of seismic actions in the best period. Given the extreme value of stress, the calculation results obtained by the pseudo-static method for the tower top are small. By contrast, the stress value for the top part of the inlet tower is large, and the calculation result obtained by the response spectrum method is relatively reasonable. The stress values at the intersection of the tower body and the slope of the rock on the right bank, the intersection of the tower body and the rock mass and the bottom of the tower body are large. The response spectrum method has certain advantages, and the calculated stress value at the weak position is relatively safe, as shown in table 1 and table 2.

Table 1 Summary of extreme values of displacement under seismic conditions of the tower body

Seisic condition	Displacement (Unit:mm)					
	U_x	Position	U_y	Position	U_z	Position
Pseudo-static method	13.93	Bent top	22.75	Bent top	6.07	Hoisting machine bottom beam
Response spectrum method	17.39	Bent top	30.65	Bent top	4.47	Hoisting machine bottom beam

Table 2 Summary of extreme values of stress under seismic conditions of the tower body

Seisic condition	Stress (Unit: MPa)											
	σ_{xmax}	Position	σ_{xmin}	Position	σ_{ymax}	Position	σ_{ymin}	Position	σ_{zmax}	Position	σ_{zmin}	Position
Pseudo-static method	1.50	Tower top	-5.80	Tower body intersects with the left bank rock	2.60	Tower top	-7.10	Tower top	4.00	Tower body intersects with the right bank rock	-11.10	Tower body intersects with the right bank rock
Response spectrum method	5.20	Tower top	-1.00	Downstream tower body intersects with the rock mass	7.20	Tower top	-2.10	Tower body intersects with the right bank rock	2.00	Tower body intersects with the right bank rock	-0.90	Tower bottom

Note: The tensile stress is positive, and the compressive stress is negative.

The table shows that the stress value at the top of the tower body is large and that a certain stress concentration exists. The intersection of the top of the upstream bank of the intake tower and the bottom of the bent part is taken as the starting point of the stress path. The maximum principal stress at the intersection of the bottom of nine columns and the top of the tower is extracted clockwise downstream. Figure 12 shows the changes of the principal stress at the intersection of the tower top and the bent bottom of the intake tower under normal water storage conditions obtained by the pseudo-static method and the response spectrum method in the context of an earthquake.

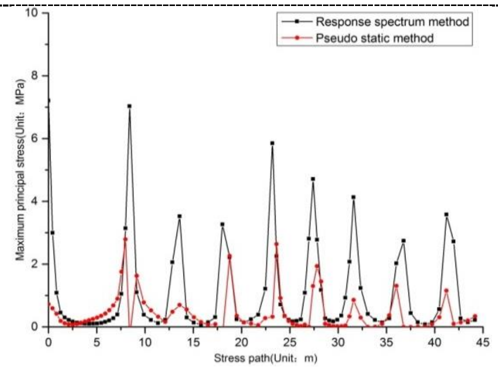

Figure 12. Variation law of the maximum principal stress at the top of the tower body

Nine stress peaks are observed (Figure 12), i.e. the stress value at the intersection of the nine columns and the tower top. The maximum value obtained by the response spectrum method at the intersection is 7.2 MPa, and the maximum value obtained by the pseudo-static method is 2.6 MPa. For the pseudo-static method, the dynamic characteristics of the load can be reflected within a certain range, but the dynamic performance of the structure itself and the dynamic response between the structures cannot be well reflected. By contrast, the response spectrum method can reflect the peak response of earthquakes generated in different time periods to effectively capture the actual peak response. The calculation results obtained by the response spectrum method at this position are relatively safe, can effectively reflect the stress concentration and the actual dynamic performance of the structure.

5. Conclusion

Both methods have advantages and disadvantages. The calculation result obtained by the pseudo-static method is safer than that obtained by the response spectrum method. The response spectrum method can effectively reflect the weak position of the intake tower. However, in the case of structural analysis and contact with surrounding rocks, a large difference between the two methods exists. A comparison of the pseudo-static method and the response spectrum method shows that their displacement results are similar and that the positions of the extreme values are the same. However, the calculation results of the two stresses are different, as reflected in the three directions of X, Y and Z. The extreme values of the compressive stress and those of the tensile and compressive stresses in the three directions are different.

Acknowledgments

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