

Article

Dynamic Response Analysis of Intake Tower-Hydrodynamic Coupling Boundary Based on SV Wave Spatial Incidence

Xiaodong Zheng ^{1,2}, Yiming Shen ^{1,2}, Xingguang Zong ^{3,*}, Hui Su ^{1,2,*} and Xun Zhao ⁴

¹ College of Water Resources and Hydropower, Hebei University of Engineering, Handan 056001, China; zhengxiaodong@hebeu.edu (X.Z.); shenyiminghue@outlook.com (Y.S.)

² Hebei Key Laboratory of Intelligent Water Resources of Hebei Province, Handan 056038, China

³ Hebei Province Water Conservancy Engineering Bureau Group Co., Ltd., Shijiazhuang 050021, China

⁴ Hebei Hydraulic Research Institute, Shijiazhuang 050000, China; zhaoxunhebei@outlook.com

* Correspondence: zongxingguang@outlook.com (X.Z.); suhui@hebeu.edu.cn (H.S.)

Abstract: In view of the insufficient analysis of the coupled joint seismic response of the intake tower–reservoir water–foundation boundary under the oblique incidence of SV wave space, a three-dimensional dynamic equation of the oblique incidence of SV wave space is established in this paper. The external wave input method of viscoelastic artificial boundary combined with equivalent load and the acoustic medium theory are used to simulate the action of reservoir water, and the angle change in the SV wave incidence is realized by controlling the incident vector. The dynamic response of the structure is analyzed and the dynamic response characteristics of the structure at different incidence angles are discussed. The results show that the dynamic response and damage degree of the intake tower decreases first and then increases with the change in angle. When the vertical incidence is 0°, the maximum displacement drop is 82.05%, and the displacement response of the intake tower is more sensitive to the change in SV wave incidence angle. When SV wave is vertically incident at 0° and 35° (near the maximum critical angle of incident), the dynamic response, dynamic water pressure, damage diffusion velocity, damage area, and damage degree of the intake tower are relatively large, which seriously affects the safety and stability of the intake tower. Therefore, the influence of the oblique incidence should be considered comprehensively in the aseismic stability design of the water intake tower to provide a new idea for the safety evaluation of the same type of engineering.



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Keywords: SV wave oblique incidence; artificial dynamic boundary; acoustic unit; hydrodynamic pressure; damage characteristics

1. Introduction

The water intake tower is generally a tall hollow rectangular reinforced concrete structure independent of the reservoir. There is a flowing water body that does not exceed the height of the tower. There are complex interactions between water and foundation [1–3], and between foundation and structure [4–6]. According to the earthquake damage survey, when the source depth is shallow, the seismic wave of a near-field strong earthquake is usually oblique incident at a certain angle. However, most of the current studies on the coupled resonance response of the intake tower, water body, and foundation assume the vertical incidence of seismic wave, and often ignore the exploration on the dynamic response law and water pressure distribution of the intake tower under the oblique incidence of a seismic wave when strong earthquakes occur. In this instance, the structure of the intake tower is damaged, so it is necessary to consider.

With the progress of domestic scholars on the artificial boundary of ground motion, Liu [7] transformed the input mode of ground motion into the problem of wave source, and transformed the ground motion load into the input of equivalent node load, providing important ideas and theoretical basis for the oblique incidence of corner points.

Zhang et al. [8] discussed the dynamic response of P wave and SV wave to tunnel entrance section of rock mass, summarized the difference of incident angles of P wave and SV wave, and proposed that under the same seismic intensity, SV wave would cause more damage to tunnel structure than P wave. Zhang et al. [9] studied the dynamic interaction analysis of a subway station–soil-adjacent surface frame structure when the SV wave is oblique incident, and summarized the dynamic response of the frame structure when SV wave is vertically incident and the incident angle is about 10° in hard class II and III sites. LYU et al. [10] studied the effect of the oblique incidence of SV wave on nonlinear seismic response of arch tunnel, and the results show that the tunnel dynamic response increases with the increase in incidence angle. Most of the above scholars have studied the dynamic response law analysis and theoretical research of underground structures when near-field earthquakes occur, but there are obvious deficiencies in the near-site seismic dynamic analysis of above-ground structures.

With the development of the research process, most scholars begin to pay attention to the study of the dynamic response of ground structures when near-field earthquakes (mainly SV wave and P wave) occur. Wang [11] and Liu et al. [12] studied the response characteristics and tensile damage evaluation of asphalt concrete core wall under the oblique incidence of SV wave space and summarized the spatial distribution law of acceleration of the concrete core wall under the oblique incidence of the SV wave space. Seiphoori et al. [13] studied the seismic response of faced rockfill DAMS under different incidence angles of P wave, SV wave, and SH wave, providing a new research idea for the study of structural dynamic response laws of above-ground hydraulic structures under different waveforms. Li et al. [14] studied the plastic damage response analysis of concrete gravity DAMS under oblique incidence of seismic waves, and concluded that the dynamic response under oblique incidence of ground motion is significantly different from that under horizontal and vertical incidence. They proposed that the maximum response of displacement, stress, and damage is reached when the P wave is incident at 60° , and SV wave is incident at 0° ; therefore the necessity of considering the incidence angle is proved. Sun et al. [15] studied the seismic response of a gravity dam under the oblique incidence of plane SV waves, and showed that the incidence angle makes the stress at key parts of the dam body less sensitive to the incidence angle of SV waves. When studying the above-ground hydraulic structure, the above scholars summarized the dynamic response rules of different incident waves and different incident angles to the above-ground structure, but ignored the influence of water body on the structure and the coupling resonance between water body and structure. Li et al. [16,17] studied the impact of dynamic water pressure distribution on a dam surface and the dynamic response of a dam body based on sound-solid coupling analysis of arch dam–reservoir water–foundation interaction, but did not consider the coupling resonance between structure and water body during near-field earthquakes.

So far, most scholars have focused on the damage and destruction of structures caused by oblique incidence of seismic waves, and summarized the effects of different incident waves and incidence angles on structures. However, the coupled co-seismic action of special hydraulic structures surrounded by water, such as water intake towers, has been ignored, resulting in conservative evaluation of structural dynamic response under oblique incidence of seismic waves. Therefore, it is necessary to analyze the dynamic response law of the dynamic coupling boundary between water body and structure under the oblique incidence of seismic wave space.

In view of the lack of research on the dynamic response analysis of the coupled seismic shock of intake tower–reservoir water–foundation under oblique incidence of seismic waves, this paper carries out the analysis of the overall dynamic response and damage development characteristics of intake tower–reservoir water–foundation under oblique incidence of seismic waves in space. Considering the randomness of the oblique incidence angle of earthquake waves, the three-dimensional wave equation of SV wave in space oblique incidence is established. Taking Yangqu water intake tower in southwest of our country as the study object, the dynamic response law of water intake tower under oblique

incidence of SV space is summarized. The research results can provide some reference for the safety and stability research of intake tower structure.

2. Artificial Boundary Theory and SV Wave Oblique Incidence Dynamic Equation

2.1. Artificial Boundary Theory

In order to eliminate the energy wave reflection at the boundary of the three-dimensional finite element model, this paper adopts the viscoelastic boundary [18] and the ABAQUS (2020) software through programming secondary development to convert the seismic input mode into equal force $\sigma(t)$ acting on the boundary node. Moreover, parallel grounding springs and damper elements are applied in batch at the artificial boundary of the model to achieve this. Related parameters of spring and damper components [19] and load equations of equivalent nodes are as follows [19]:

$$K_n = \frac{1}{1+A} \times \frac{\lambda+2G}{2r}, C_n = B\rho c_p \quad (1)$$

$$K_t = \frac{1}{1+A} \times \frac{G}{2r}, C_t = B\rho c_s \quad (2)$$

$$\sigma(t) = \sigma_0 + C\dot{u} + Ku \quad (3)$$

where C and K are damping coefficient and stiffness coefficient, respectively; K_n and K_t represent the spring stiffness coefficients applied to the normal and tangential sides of the boundary, respectively; C_n and C_t represent the damping coefficients of the damping element applied to the normal and tangential sides of the boundary, respectively; ρ is soil layer density; λ and G are Lamet's constants; c_p and c_s are compression wave velocity and shear wave velocity of soil, respectively. r is the distance from the scattering source to the artificial boundary; the empirical parameters A and B are 0.8 and 1.1, respectively [19]. σ_0 , $\dot{u}$, and u are the stress, velocity, and displacement at the free field node, respectively [20].

2.2. SV Wave Oblique Incident Dynamic Equation

The oblique incidence theory of SV wave is shown in Figure 1. Based on the equivalent node load theory, the time-history files of ground motion acceleration are converted into time-history files of displacement and velocity, and different incidence angles are determined through the oblique incidence dynamic equation. When the plane SV wave ($u_0(t)$ is the displacement time-history of SV wave) is the oblique incident at a certain angle at the bottom corner of the model, energy waves arriving at any point A (X_0, Y_0, Z_0) in the model are represented as directly incident SV1 waves and SV2 and P waves reflected by the ground. Local coordinate systems are established for the three kinds of energy waves as shown in Figure 1 (X^1, Y^1, Z^1), (X^2, Y^2, Z^2), and (X^3, Y^3, Z^3) [21]. The incident angle of the incident wave SV1 and the reflected wave SV2 is β , the angle of the incident wave with the X^1, X^2 axes is α , the angle of the incident wave with the Y^1, Y^2 axes is γ . The angle of the reflected wave P wave is β_p , and the angle of the incident wave with the X^3, Y^3 axes is α_p, γ_p . The angular relation of SV wave oblique incidence is shown in Figure 2.

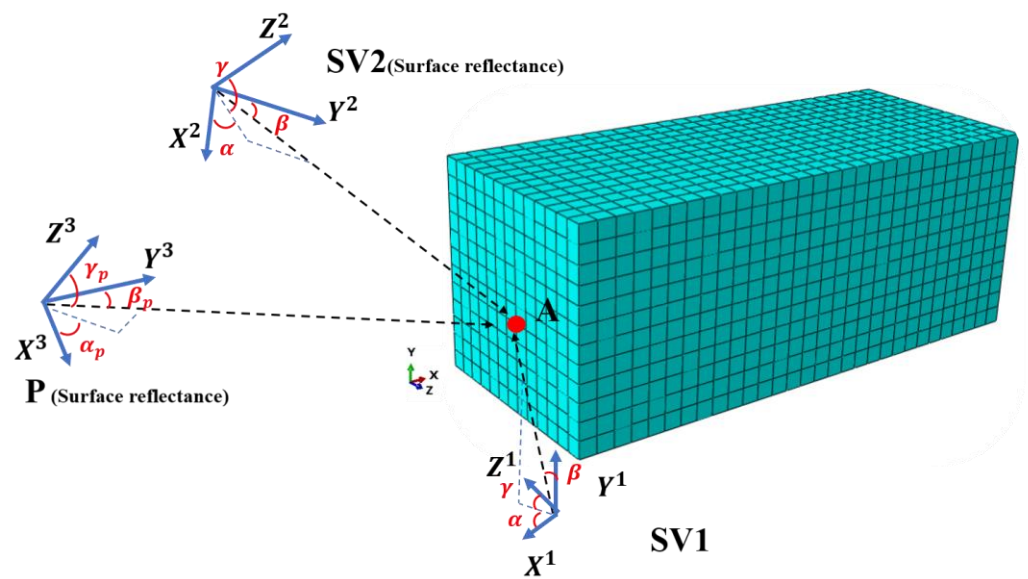


Figure 1. SV wave oblique incident local coordinates.

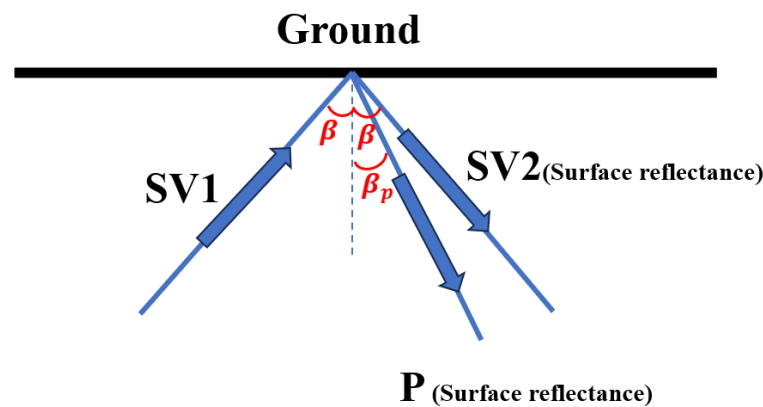


Figure 2. SV wave reflection on a free surface.

Let the angle between the direction of incident SV wave and X, Y, and Z be α , β , and γ , respectively. Where, α_p , β_p , and γ_p are the included angle of P wave. The specific formula is as follows [21]:

The transformation matrix from local coordinates (X^1, Y^1, Z^1) , (X^2, Y^2, Z^2) and (X^3, Y^3, Z^3) to global coordinates is:

$$T_1 = \begin{bmatrix} -\frac{\cos \gamma}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} & 0 & \frac{\cos \alpha}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} \\ \cos \alpha & -\cos \beta & \cos \gamma \\ -\frac{\cos \alpha \times \cos \beta}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} & \sqrt{\cos^2 \alpha + \cos^2 \gamma} & -\frac{\cos \gamma \times \cos \beta}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} \end{bmatrix} \quad (4)$$

$$T_2 = \begin{bmatrix} -\frac{\cos \gamma}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} & 0 & \frac{\cos \alpha}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} \\ \cos \alpha & -\cos \beta & \cos \gamma \\ \frac{\cos \alpha \times \cos \beta}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} & \sqrt{\cos^2 \alpha + \cos^2 \gamma} & \frac{\cos \gamma \times \cos \beta}{\sqrt{\cos^2 \alpha + \cos^2 \gamma}} \end{bmatrix} \quad (5)$$

$$T_3 = \begin{bmatrix} -\frac{\cos \gamma_p}{\sqrt{\cos^2 \alpha_p + \cos^2 \gamma_p}} & 0 & \frac{\cos \alpha_p}{\sqrt{\cos^2 \alpha_p + \cos^2 \gamma_p}} \\ \cos \alpha & -\cos \beta_p & \cos \gamma \\ -\frac{\cos \alpha_p \times \cos \beta_p}{\sqrt{\cos^2 \alpha_p + \cos^2 \gamma_p}} & \sqrt{\cos^2 \alpha_p + \cos^2 \gamma_p} & -\frac{\cos \gamma_p \times \cos \beta_p}{\sqrt{\cos^2 \alpha_p + \cos^2 \gamma_p}} \end{bmatrix} \quad (6)$$

where $\alpha_p = \arccos(\frac{\cos \alpha \times \sin \beta_p}{\sin \beta})$, $\beta_p = \arcsin(\frac{c_p \sin \beta}{c_s})$, $\gamma_p = \arccos(\frac{\cos \gamma \sin \beta_p}{\sin \beta})$.

In the local coordinate system, the displacement components caused by SV1, SV2, and P waves at point A can be expressed as:

$$[U^1] = [0 \quad 0 \quad u(t - \Delta t^1)] \quad (7)$$

$$[U^2] = [0 \quad 0 \quad A_1 u(t - \Delta t^2)] \quad (8)$$

$$[U^3] = [0 \quad A_2 u(t - \Delta t^3) \quad 0] \quad (9)$$

where A_1 is the ratio of reflected SV wave amplitude to incident SV wave amplitude; A_2 is the ratio of reflected P wave amplitude to incident SV wave amplitude; and $\Delta t^1 - \Delta t^3$ is the delay time:

$$\Delta t^1 = \frac{x_0 \cos \alpha + y_0 \cos \beta + z_0 \cos \gamma}{c_s} \quad (10)$$

$$\Delta t^2 = \frac{x_0 \cos \alpha + (Ly - y_0) \cos \beta + z_0 \cos \gamma}{c_s} \quad (11)$$

$$\Delta t^3 = \frac{(x_0 - (Ly - y_0) \cos \alpha_p / \cos \beta_p) \cos \alpha + Ly \cos \beta}{c_s} + \frac{(z_0 - (Ly - y_0) \cos \gamma_p / \cos \beta_p) \cos \gamma}{c_s} + \frac{(Ly - y_0) / \cos \beta_p}{c_p} \quad (12)$$

Through the transformation matrix, the displacement vector of point A in the total coordinate system is the superposition of the free field displacement generated by SV1, SV2, and P wave, which can be expressed as:

$$[U] = \sum_{i=1}^3 T_i [U_i] \quad (13)$$

The velocity vector in the global coordinate system can be obtained by taking the time derivative of the above equation:

$$[\dot{U}] = \sum_{i=1}^3 T_i [\dot{U}_i] \quad (14)$$

The free field stress of SV1 and SV2 in local coordinates at point A is:

$$[\sigma_{ij}^l] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \tau_{yz}^l \\ 0 & \tau_{yz}^l & 0 \end{bmatrix}, \tau_{yz}^l = \tau_{yz}^l = -\frac{G}{c_s} \dot{u}(t - \Delta t^l) \quad (15)$$

where $i = 1, 2$ represents SV1 and SV2 waves, respectively.

The free field stress of P wave at point A in local coordinate system is:

$$[\sigma_{ij}^3] = \begin{bmatrix} \sigma_{xx}^3 & 0 & 0 \\ 0 & \sigma_{yy}^3 & 0 \\ 0 & 0 & \sigma_{zz}^3 \end{bmatrix}, \sigma_{xx}^3 = \sigma_{zz}^3 = -\frac{\lambda}{c_p} \dot{u}(t - \Delta t^3), \sigma_{yy}^3 = -\frac{\lambda + 2G}{c_p} \dot{u}(t - \Delta t^3) \quad (16)$$

The free field stress of SV1, SV2 and P wave at point A under global coordinates is:

$$[\sigma_{ij}] = \sum_{l=1}^3 [T_l]^T [\sigma_{ij}^l] [T_l] \quad (17)$$

By substituting Equations (13), (14), and (17) into Equation (3), the oblique incidence equation of SV wave can be obtained. It should be noted that there is waveform conversion when SV wave is oblique incident. When SV wave is less than incident at a certain angle, the ground surface reflects SV wave and P wave at the same time; when SV wave is greater than incident at a certain angle, only SV wave is reflected at the surface, which is the critical angle of SV wave θ_{cr} , which is related to the Poisson's ratio ν and determined by the following formula [22]:

$$\theta_{cr} = \arcsin\left(\sqrt{\frac{1-2\nu}{2(1-\nu)}}\right) \quad (18)$$

In this paper, the Poisson's ratio is 0.2 and the critical incident angle is 35.1° . Therefore, in the case of SV wave oblique incidence, only the critical incidence angle of 0° to 35° is considered in this paper.

3. Finite Element Model and Calculation Parameters

3.1. Finite Element Model of Intake Tower

The intake tower of Yangqu Hydropower Station in southwest China is selected as the main research structure, and the finite element calculation model of intake tower–water–foundation is established, as shown in Figure 3c. The height of the tower is 85.5 m, and the normal water level is 74 m. The tower was fabricated of C30 concrete, and the tower body was fabricated of C25 concrete. The number of intake tower grid units is 32,445, the grid unit attribute is C3D8R, and the concrete damage model (CDP) is used.

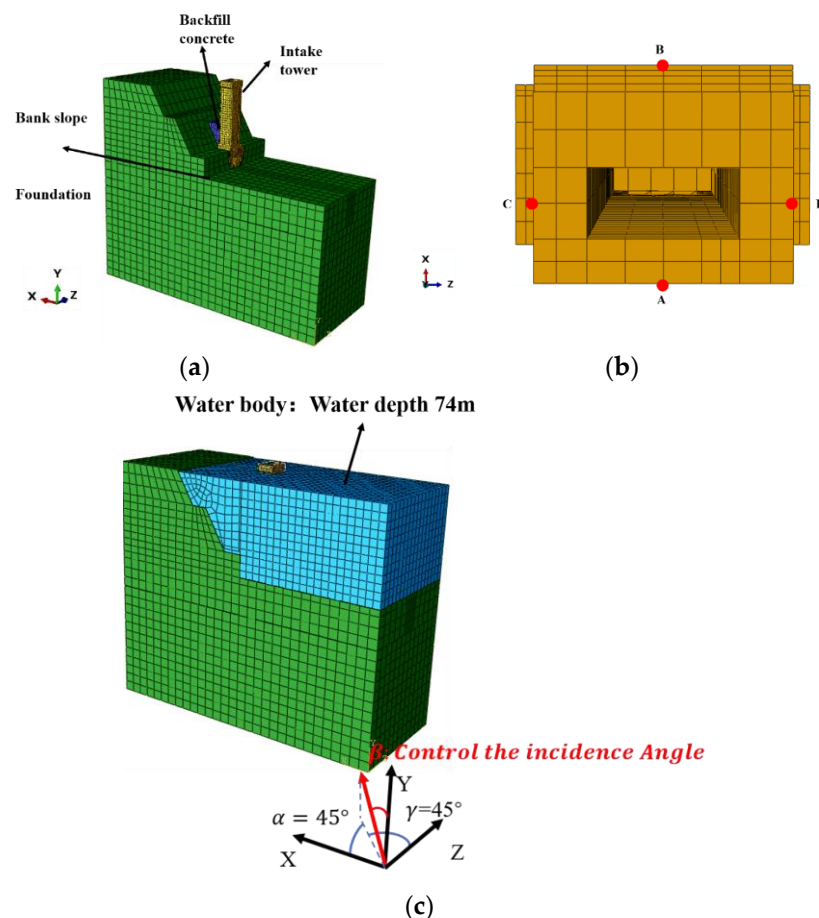


Figure 3. Specific model, overall model, and detailed structure diagram of the water intake tower. (a) Detailed structure drawing of water intake tower; (b) intake tower monitoring points; (c) integral finite element angular incidence model of water intake tower, reservoir water, and foundation.

The foundation was simulated by C3D8R units with a total of 7776 units. The water body was simulated by acoustic unit AC3D8, the total number of units was 5950. The volume modulus of reservoir water is set as 2Gpa (compressible water) [23]. Detailed material parameters are shown in Table 1. The water surface of the reservoir is set as a free surface, and the cut-off boundary of the reservoir water is set as an absorption boundary so that the hydrodynamic pressure wave does not produce a rebound wave at the tail, which is used to simulate the radiation damping effect. The tie constraint is used to simulate the coupling effect between the acoustic medium and the structure at the contact surface of intake tower-reservoir water and ground-reservoir water. The overall three-dimensional finite element model and the finite element model of the water intake tower are shown in Figure 3.

Table 1. Structural material parameter values of each part of the water intake tower.

Material	Density (kg/m ³)	Elasticity Modulus (MPa)	Poisson's Ratio
Tower body	2500	2.8×10^4	0.167
Tower base	2500	3.0×10^4	0.167
Foundation	2720	1.5×10^4	0.2

Due to the extremely special aspect ratio of the water intake tower, it has the problem of a whipping effect. In this paper, four central points on the top of the water intake tower, A (water intake surface on the top of the water intake tower), B (rear side of the top of the water intake tower), C (left side of the top of the water intake tower), and D (right side of the top of the water intake tower), are taken as monitoring points for dynamic response analysis, as shown in Figure 3b. Using the vertex at the bottom of the foundation as the incident angle, the angle α and γ between the SV incident wave and the X and Z axes are determined, and the incident angle is controlled by the incidence vector [0.000, 1.000, 0.000], [0.110, 0.987, 0.110], [0.218, 0.951, 0.218], [0.320, 0.891, 0.320], and [0.405, 0.819, 0.405] to carry out the SV wave oblique incidence. See Figure 3c of the incidence angle for details.

3.2. Incident Wave Parameters and Selection

Yangqu Hydropower Station is a first-class large (1) project, and the spillway tunnel intake tower is Grade 1. The seismic fortification category of spillway tunnel inlet tower project is Class A, the basic intensity of earthquake is 7 degrees, and the fortification intensity is 8 degrees. The inlet tower of the spillway tunnel is designed as a level-1 retaining structure. The ground motion parameter with the exceedance probability of $p_{100} = 2\%$ in 100 years during the base period is taken as the design earthquake. The corresponding peak acceleration of the horizontal ground motion of the bedrock is 0.304 g, and the characteristic period T_g is 0.2 s. The maximum acceleration of the design response spectrum is $\beta_{max} = 6.71 \text{ m}\cdot\text{s}^{-2}$). According to the suggestion of seismic design response spectrum, the time–history curve of acceleration, displacement, and velocity of the artificial seismic wave can be fitted: the total duration is 20 s, and the time step is 0.01 s. The seismic incident wave is shown in Figure 4.

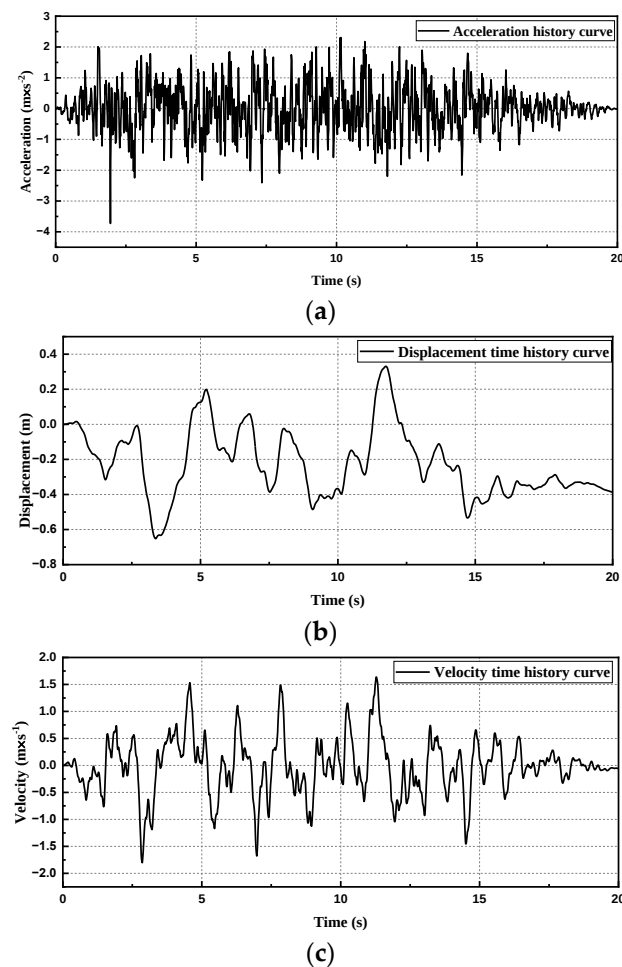


Figure 4. Design of artificial seismic waves. (a) Acceleration time-history curve; (b) displacement time-history curve; (c) velocity time-history curve.

4. Results and Analysis

4.1. Displacement and Acceleration Response Analysis

Figures 5 and 6 show the maximum peak displacement and absolute value of acceleration of each monitoring point at the top of the water intake tower under different incident angles of SV wave. It can be seen from Figures 5 and 6 that the incident angle of SV wave has a significant influence on the maximum displacement and acceleration amplitude of the intake tower.

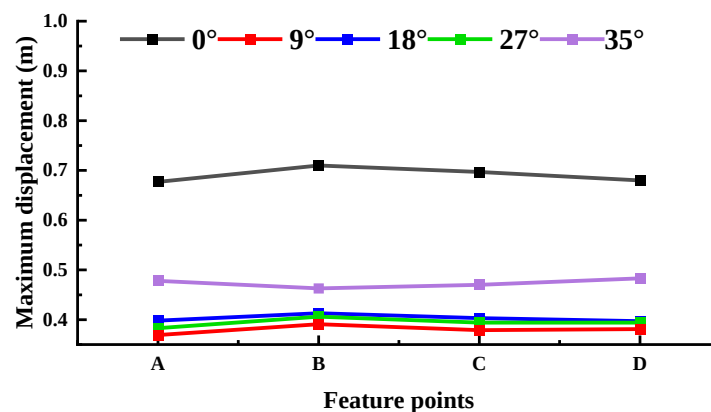


Figure 5. Maximum displacement curve of monitoring point.

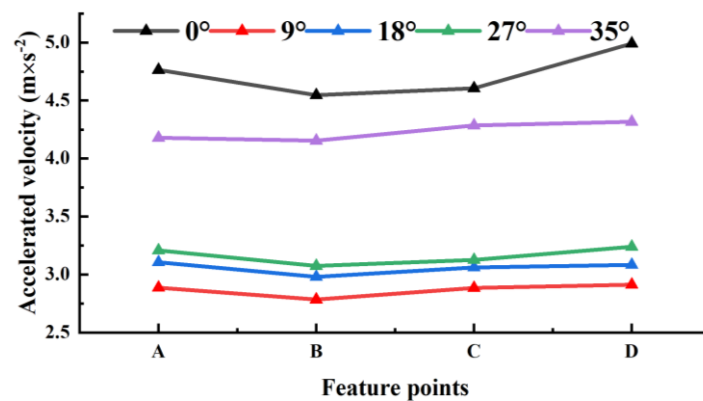


Figure 6. Curve of absolute value of maximum acceleration at monitoring point.

When the SV wave is the oblique incident, the displacement and acceleration responses of each key point of the tower are shown in Figure 5. It can be seen from Figures 5 and 6 that, when the SV wave is vertically incident at 0° , the displacement and acceleration responses of the intake tower reach the maximum values of 0.71 m and $4.99\text{ m}\cdot\text{s}^{-2}$, respectively, which greatly affect the safety and stability of the tower. At 9° oblique incidence, the minimum displacement response and acceleration response of the intake tower are 0.39 m and $2.78\text{ m}\cdot\text{s}^{-2}$, respectively, and the maximum decrease occurs at this time, decreasing by 82.05% and 79.49% , respectively. This indicates that the displacement response of the intake tower is sensitive to the incidence angle. At 18° and 27° oblique incidence, the response values of the displacement and acceleration of the intake tower are very close to each other. At 35° oblique incidence, the displacement and acceleration response values of the intake tower are 0.48 m and $4.31\text{ m}\cdot\text{s}^{-2}$, respectively, and at the same time, the maximum increase occurs, increasing by 23.07% and 55.03% , respectively, which has a great impact on the safe operation of the intake tower. To sum, the relation curve of the displacement and acceleration response of the intake tower structure with the change in angle shows an overall trend of decreasing first, leveling off and then increasing. The maximum decrease and increase occur at 0° vertical incidence and 35° oblique incidence, respectively, which seriously endangers the safety of the tower. Therefore, it is suggested to take SV wave 0° vertical incidence and 35° oblique incidence as the most unfavorable conditions for seismic response of intake tower.

4.2. Stress Analysis

The first stress (principal tensile stress) peak value of intake tower is extracted to evaluate the stress state of intake tower structure, as shown in Figure 7 and Table 2. When SV wave is vertically incident at 0° , the maximum tensile stress value of the intake tower is 3.21 MPa , which greatly endangers the safe and stable operation of the intake tower. When the SV wave is oblique incident at 9° , the main tensile stress of the intake tower is the minimum, and the minimum value is 1.98 MPa . At this time, the stress state of the intake tower has the largest decrease, decreasing by 61.78% . When the SV wave is oblique incident at 18° and 27° , the principal tensile stress has little change, and the principal tensile stress shows a stable excessive trend. When the SV wave is oblique incident at 35° , the maximum tensile stress of the intake tower is 2.70 MPa , and the maximum increase in the intake tower is 35.95% . This shows that when the incidence angle is close to the critical angle of incidence, the stress state of the intake tower structure is more unfavorable, and the intake tower stress surges, causing great harm to the safety of the intake tower.

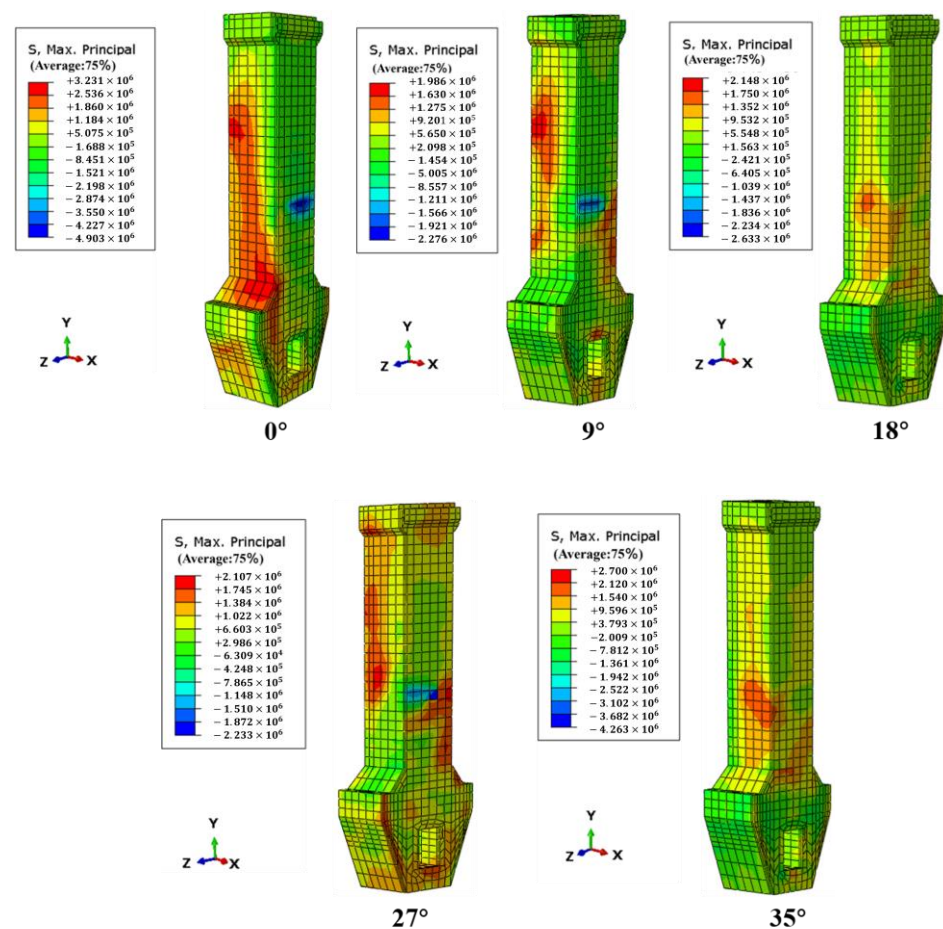


Figure 7. Stress distribution figures.

Table 2. Stress extremes under different working conditions.

Angle (°)	Tensile Stress (MPa)	Compressive Stress (MPa)
0°	3.21	4.90
9°	1.98	2.27
18°	2.14	2.63
27°	2.10	2.23
35°	2.70	4.26

SV wave at 0°, 9°, 18°, 27°, and 35° oblique incidence angle, the main tensile stress of the intake tower with the change in incidence angle presents the overall trend of first decrease and increase, the spatial distribution characteristics of the intake tower stress are consistent, the peak stress location mainly exists in the right side of the tower, and the tower interface. When SV wave is 0° vertical incidence and 35° oblique incidence, the stress state of the intake tower appears the largest decline and increase, which makes the stress state of the intake tower undergo drastic changes. Therefore, it is easier to introduce the stress concentration of the water tower, resulting in tensile crack damage.

4.3. Analysis of SV Wave Oblique Incident Dynamic Water Pressure

The dynamic water pressure distribution diagram of each facing water surface under the effect of coupled vibration between the intake tower and the water body is presented in Figure 8, when SV wave is incident at $\beta = 0^\circ, 9^\circ, 18^\circ, 27^\circ, 35^\circ$ successively. The downstream and vertical flow directions' dynamic water pressure of the intake tower are analyzed by extracting its values at different incidence angles. From Figure 8, it is evident

that the vertical direction of the water inlet tower experiences the highest mean value of dynamic water pressure under different angle incidences, followed by the forward direction and then the back. The distribution pattern of dynamic water pressure on the exterior surface outside the inlet tower is generally consistent, with a parabolic trend observed in the outer complex line. The dynamic water pressure at the water surface remains negligible, while it increases proportionally with increasing depth. When the SV wave is incident at 9° , 18° , 27° , and 35° angles, the dynamic water pressure on each facing surface exhibits a linear relationship with the incidence angle. Furthermore, as the angle increases, so does the dynamic water pressure. When SV waves are incident obliquely at an angle of 9° , the hydrodynamic pressure reaches its minimum value. The SV wave exhibits a hydrodynamic pressure value that is closely approximated at oblique incidence angles of 18° and 27° . When the SV wave is incident at 0° and 35° , the hydrodynamic pressure exerted on each facing water surface reaches its maximum, posing a significant threat to the safety and stability of the intake tower.

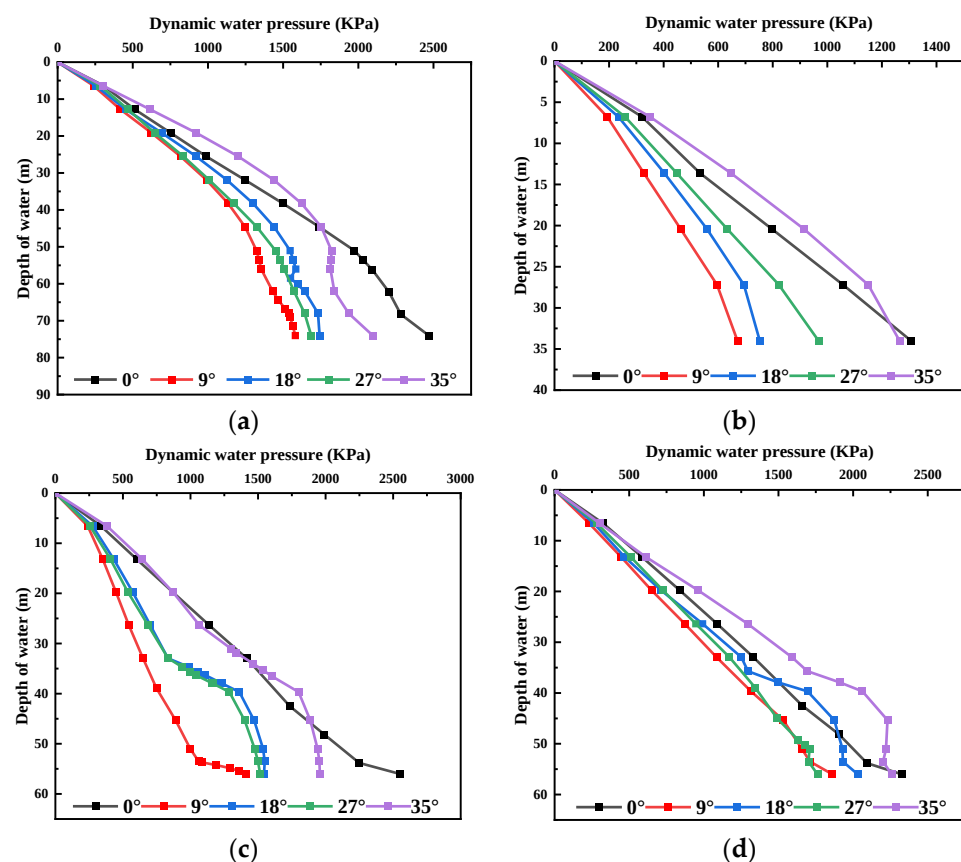


Figure 8. Hydrodynamic pressure distribution diagram figures. (a) Water inlet surface; (b) rear side of the tower; (c) left side of the tower; (d) right side of the tower.

To conclude, the maximum hydrodynamic pressure value occurs when an SV wave is incident vertically at a 0° angle. As the incidence angle approaches the critical angle of SV wave, there is a gradual increase in hydrodynamic pressure. Therefore, it is recommended that the coupled vibration response of water bodies be analyzed with caution under SV wave incidence at 0° vertical and 35° oblique angles near the critical angle.

4.4. Damage Characteristics Analysis of SV Wave Oblique Incident Water Intake Tower

In this paper, the angle of Y-axis $\beta = 0^\circ, 9^\circ, 18^\circ, 27^\circ, 35^\circ$ is taken as the research variable to carry out the oblique incidence angle of SV wave, and the damage characteristics of the intake tower under different incidence angles are studied, and the results are shown in Figure 9. SV wave at 0° vertical incidence and $9^\circ, 18^\circ, 27^\circ$, and 35° oblique incidence

under the action of damage degree and damage area difference is obvious, when SV wave at 0° and 35° oblique incidence, the tower damage is the most serious, the damage area reaches the maximum, and the change is more drastic.

When the seismic action is 3.45 s, the inlet surface of the water intake tower shows preliminary damage under the incidence of SV wave at 0° angle. When the SV wave incident at an angle of 35° , the initial damage appears in a certain range at the bottom of the inlet surface of the water intake tower and has a trend of extending from the right side of the bottom of the inlet surface to the left side to form a through. At the same time, when SV wave incident at 9° , 18° , and 27° oblique angle, the seismic load of the intake tower is 3.45 s, the damage appears initially, but the damage trend is not obvious.

Under the earthquake action of 5 s, SV wave with 9° , 18° , and 27° oblique incidence at the water inlet surface of the initial damage site gradually increased and there was a trend of upward penetration at the bottom of the base, the damage area also gradually spread to the tower and the base joint. When the SV wave with 35° oblique incidence, the damage area in 9° , 18° , and 27° oblique incidence along the tower side to the upper diffusion, the diffusion trend is more obvious compared with 9° , 18° , and 27° oblique incidence, and the damage range is larger. When the SV wave has 0° vertical incidence, the damage development increases dramatically, from the preliminary damage position transferred to the water intake tower and the base of the connection, and to the tower above the diffusion, the damage diffusion trend is obvious, the damage diffusion speed is fast, and the damage range is large.

When the earthquake acts for 10 s, SV wave with 9° , 18° , 27° , and 35° oblique incidence under the action of the damage of the water intake tower in the rear of the tower body and the backfill concrete interaction facing the tower body around the small range of diffusion, the damage area through the two sides of the tower to the upstream surface further diffusion, the damage degree is further aggravated. Compared with SV wave with 0° vertical incidence, the 0° vertical incidence model in the rear of the tower body and backfill concrete interaction around the tower body is greatly diffused, the damage area through the two sides of the tower to the upstream surface is further diffused, the front damage intensifies, and the damage degree further intensifies, the damage area is the largest and more intense.

When the earthquake action is 18 s, the damage of each part of the water intake tower with different incidence angle models no longer diffuses and intensifies. When SV wave is at 9° , 18° , and 27° oblique incident, the damage area does not continue to spread to the tower and tower joint, but the damage degree is further aggravated. When the SV wave is 0° and 35° incident, the damage area of the water intake tower by the tower and tower joint continues to the rear of the tower and the interaction of the backfill concrete and the tower on both sides of the upstream surface diffusion, the damage degree and damage area reaches the maximum, which is the most severe at 0° vertical incidence, there is a variety of angle incidence under the action of the maximum damage area.

In practical engineering, buildings such as water intake towers can be monitored on-line for structural health [24] by some scientific means, and detected for structural damage development based on dynamic response and dynamic real-time detection technology [25]. Effective monitoring of structural health status and damage degree can ensure safe and stable operation of structures. It not only provides the basis for the reliability evaluation of the structure after the earthquake, but also guarantees the safety of people's life and property.

According to the above analysis, SV wave with 9° , 18° , and 27° oblique incidence has no increase in damage in the early stage; when the time is the same, the damage degree and damage area of the intake tower is positively correlated with the trend of angle, and with the increase in angle becomes more intense, the diffusion speed of damage area is also rapidly increases with the increase in incidence angle. When the SV wave is 0° vertical incidence and 35° oblique incidence, the damage occurs mainly at the interface between the intake tower and the tower. Compared with 9° , 18° , and 27° oblique incidence, not only damage occurs at the rear of the tower and the backfill concrete interaction surface,

but also severe damage occurs at the interface between the tower body and the tower base. The reason why the damage occurs in these two places is that the change in the external structure makes the intake tower more prone to stress concentration and thus damage. Moreover, the strength of the tower body and the tower base material is inconsistent, so the stiffness changes and damage occurs. To sum, when the SV wave is 0° vertical incidence and 35° oblique incidence, the damage degree and area of the water intake tower are the most severe, and the damage area spreads the fastest, causing the greatest harm to the safe and stable operation of the water intake tower.

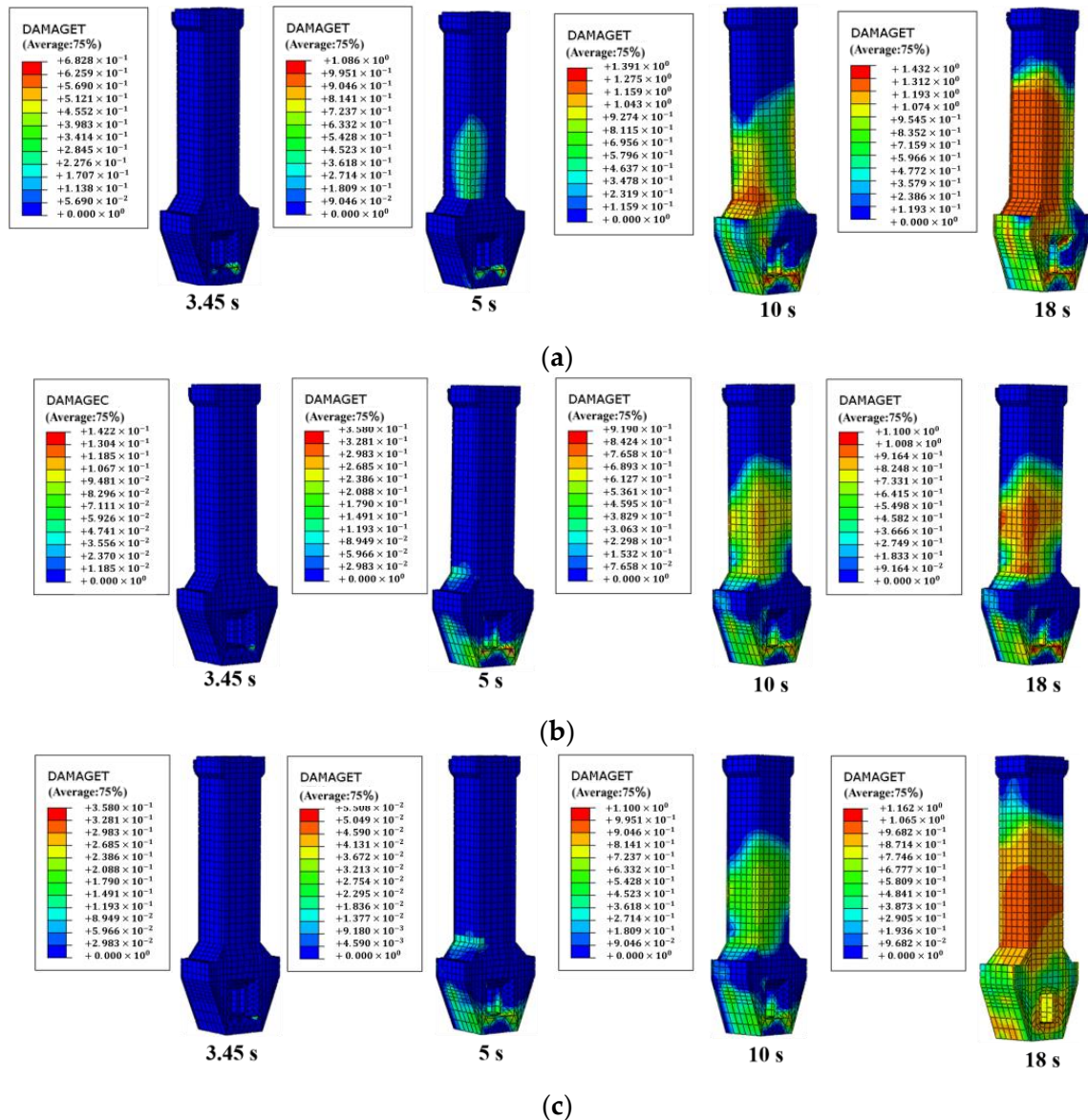


Figure 9. Cont.

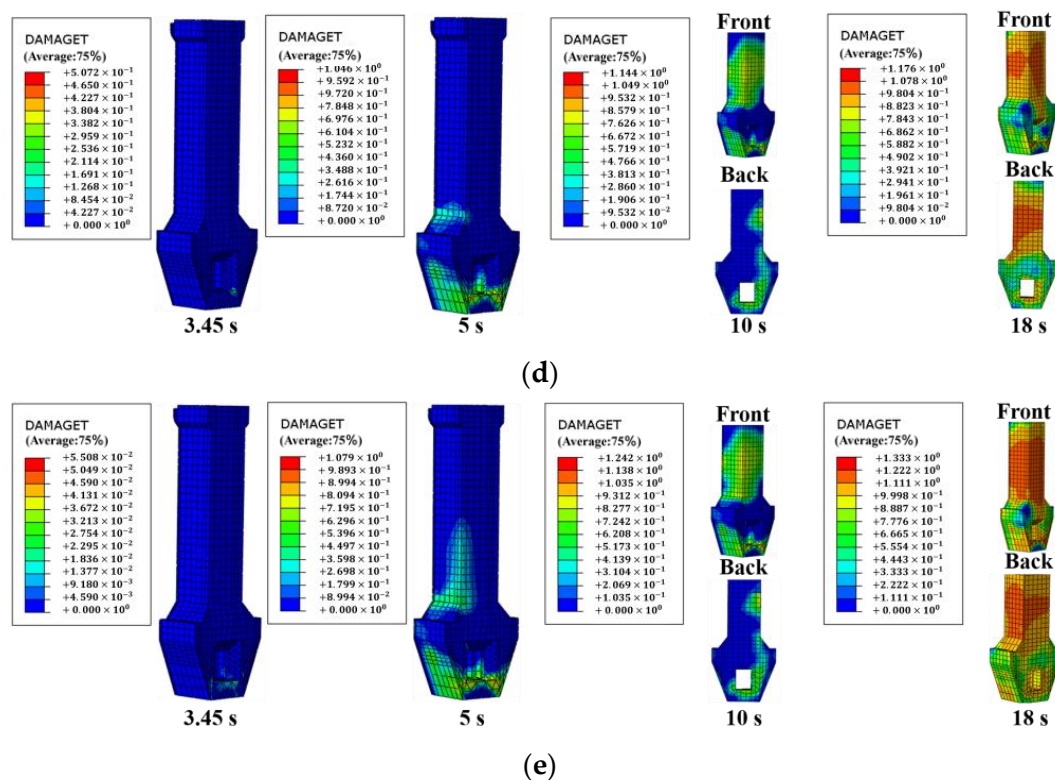


Figure 9. Nonlinear damage diagram of water intake tower at different incidence angles. (a) SV wave is vertically incident at 0° ; (b) SV wave 9° oblique incidence; (c) SV wave 18° oblique incidence; (d) SV wave 27° oblique incidence; (e) SV wave 35° oblique incidence.

5. Conclusions

Based on viscoelastic artificial boundary and equivalent node load theory, instead of the traditional seismic wave input method, the dynamic equation of the three-dimensional integral finite element model of intake tower–reservoir water–foundation under the oblique incidence of SV wave is established in this paper, from the aspects of the intake tower displacement response, acceleration response, stress state, hydrodynamic pressure, damage, and so on. The dynamic response of SV wave to the coupled boundary of water intake tower is analyzed. The main conclusions are as follows:

- (1) According to the ground motion load condition of the water intake tower in this paper, when the SV wave is vertically incident at an angle of 0° , each dynamic response reaches its maximum value; when its oblique incident is at 9° , each response reaches its minimum value; when its oblique incident is at 35° , each response is slightly less than 0° . The displacement response, acceleration response, and stress state of the intake tower decrease first and then increase as the angle changes. At 0° vertical incidence and 35° oblique incidence, the maximum decrease and increase in the displacement, acceleration response, and stress state of the intake tower appear, which has a great impact on the dam body safety, mainly manifested in the tower position shift response decrease of 82.05% and the maximum acceleration response increase of 55.03%. This indicates that the displacement response of the intake tower is sensitive to the change in SV wave incidence angle.
- (2) According to the ground motion load condition of the water intake tower in this paper, when the SV wave incident is at different angles, the dynamic water pressure distribution on each oncoming surface is similar, showing a parabolic distribution law, and increases with the water depth; when SV wave is vertically incident at 0° , the peak pressure of dynamic water reaches the maximum value. When SV wave

is oblique incident at 35° , the mean value of dynamic water pressure changes with water depth is the maximum.

- (3) According to the ground motion load condition of the water intake tower in this paper, the damage location of the intake tower under the oblique incidence of SV wave is mainly concentrated in the rear of the tower and the interaction surface of the backfill concrete and the interface between the tower body and the tower base. The results of tensile damage show that under the same seismic intensity, the damage diffusion velocity, damage area, and damage degree of SV wave are the most rapid, extensive, and intense under 0° vertical incidence and 35° oblique incidence. Therefore, when designing the stability of hydraulic structure, the dynamic response of SV wave incident at 0° angle and incident at critical angle should be mainly considered.

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