Numerical Analysis of Flow-Induced Vibration of Deep-Hole Plane Steel Gate in Partial Opening Operation

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Abstract: Hydraulic steel gates are the core adjustment mechanism for water conservancy projects, the safety of which is related to the safety of the entire water conservancy project. In this study, the issue of flow-induced vibration under the influence of pulsing water pressure when the deep-hole plane steel gate construction is partially opened is investigated using a numerical calculation approach of CFD–CSD coupling. The time-history pulsating pressure loads of each part are first determined by tracking the upstream, bottom, and downstream pulsating water pressure loads under partially open operation conditions of the gate. The impact of the water in front of the gate on the natural vibration mode and frequency of the gate is then investigated based on the analysis of the dry/wet modes of the gate structure. Additionally, the hydrodynamic load is applied to the finite element model of the gate structure while taking into account the fluid–structure coupling effect, and the results of the gate flow-induced vibration response are obtained. Three typical local opening relative openings are chosen, with the operating state of the design water head (Hs = 70 m) of a deep-hole plane steel gate as an example. According to the analysis’s findings, the gate’s natural vibration frequency is greatly lowered under the influence of the water in front of it, and its amplitude increases by 50%. The pressure value pressing on the gate changes dynamically as it is partially opened and discharged. The maximum dynamic displacement value and the maximum dynamic stress value of the gate both appear in the middle and lower part of the gate under the condition of partial opening, and both occur when the relative opening is e/H = 0.125. The maximum displacement value is 3.43 mm, and the maximum stress value is 161 MPa. The maximum dynamic displacement and dynamic stress of each gate component steadily decrease with an increase in the relative openness. The gate dynamic response analysis approach described in this research can serve as a guide for hydraulic engineering design.

Keywords: deep-hole plane steel gate; numerical analysis; dynamic characteristics; hydrodynamic load; dynamic response

1. Introduction

Hydraulic plane steel gates play an important role in water flow regulation and storage in water conservancy projects. They are extensively used in water conservancy and hydropower projects due to their simple and reliable structural design, low manufacturing, easy installation, and relative ease of transportation [1–3]. In operating conditions, the hydraulic plane steel gates are partially opened, and flow-induced vibration occurs under the dynamic water pressure generated by the water flow. When the vibration is severe, the gate structure is induced to fail, causing damage. With the quick increase in the number of high-dam and large-scale reservoirs, particularly for deep-hole plane steel gates, due to the asymmetrical water flow, the flow-induced vibration, and high water pressure, the energy of the pulsating pressure is high, making the flow-induced vibration problem more clear.

Hydraulic steel gates vibrate due to flow, which is a complicated mechanical process [4]. The excitation mechanism of gate vibration is complex and variable as a result of the...
combined action of internal and external factors, such as the natural vibration frequency of the gate, the structural stiffness of the gate, the spectral characteristics of the pulsating water flow, etc. [5–7]. The existing gate flow-induced vibration analysis method mainly judges whether the water body and the structure resonate by comparing the pulsating water pressure frequency and the natural vibration frequency of the structure, further estimating whether the structure design is safe and reasonable [8]. At present, the flow-induced vibration analysis of hydraulic steel gate mainly adopts the methods of prototype observation, model testing and numerical simulation analysis [3]. Limited by the influence of sensors and the environment, prototype observation of deep-hole gates is difficult and cannot predict the dynamic changes of the gate. Physical model testing is difficult and costly to design and perform due to limitations associated with the similarity of the material, structure, geometry, physics and mechanics of the scaled physical model. Thus, physical models are not preferable, as their analysis cannot meet the accuracy requirements. The numerical simulation method of fluid–structure interaction based on methods such as the finite element method has a low time cost and strong operability and is suitable for flow-induced vibration analysis of hydraulic gates.

Scholars have achieved satisfactory results with respect to the flow-induced vibration response of gates. Liu. Y. [9] and Jiao. X. [10] used ANSYS to study the structural vibration characteristics of gates in water or under waterless conditions. The vibration response of gates was studied using transient time-history analysis. Xu. Z. [11] used the three-dimensional boundary element numerical analysis method to analyze a plane-fixed wheel gate, considering the influence of the “additional mass” caused by the fluid–structure coupling on the natural vibration characteristics, and further analyzed the natural vibration frequency and mode. Gu. H. [12] analyzed the flow-induced vibration characteristics of a gate based on the finite element method, determining the effect on the natural vibration frequency of the water length in front of the gate. Li. H. [13] studied and analyzed the flow-induced vibration characteristics of deep-hole plane gates by combining model testing and numerical simulation and proposed the unfavorable opening degree of gate operation. Based on model testing and numerical simulation of flow-induced vibration, Pan. S. [14] applied the time-history of pulsating water pressure of a plane gate obtained by testing the gate structure and used the generalized Newmark-β method to solve the kinetic equations to obtain analysis result on the vibration time-history of the gate structure. On the basis of a hydraulic model test, Zhao. L. [15,16] used the numerical simulation method to study the flow-induced vibration characteristics of a large plane gate and radial gate and analyzed the vibration response of various gate opening heights. Guo. G. [17] established a mathematical model to study the vertical vibration mechanism and vibration stability of a plane gate, which was verified by numerical simulation, and proposed a stability index of the vertical self-excited vibration of the gate. Yan. G. [18] analyzed the random vibration response of a gate structure through experimental modal analysis and finite element calculation, suggesting that optimizing the structural characteristics of the gate can effectively improve its antivibration performance.

Xu. C. [19–21] conducted research on the dynamic stability of a gate structure, drawing conclusions about gate vibration. Wang et al. [22] studied the vibration and holding force characteristics of a plane gate during the closing process by means of model tests and numerical simulation methods and determined the influence of the creeping vibration of the plane gate during the discharge process. In summary, many studies have investigated the flow-induced vibration of gates, mainly via research methods that combine model tests and numerical simulation methods. The test period required for such methods is long and limited by problems such as model scale. The main reason for using model testing is that the current theoretical research on dynamic water pressure in the gate area is limited by the instability of high-speed water flow. The flow-induced vibration response of the hydraulic steel gate structure is related to the characteristics of hydrodynamic loads acting on the gate structure characteristics. Few studies have been conducted to date involving dynamic characteristic analysis and investigating the dynamic response of partial opening
operation of deep-hole plane gates. It is particularly important to establish a numerical analysis method of flow-induced vibration of the gate structure and to evaluate the safety of deep-hole plane steel gate under partially opened operation.

With the development of computational fluid dynamics, numerical models have been widely used to simulate water flow characteristics, solving some flow field analysis problems. Zhang, J. [23], Chen, Y. [24] and others used the RNG $k-\varepsilon$ model and the VOF method to numerically simulate and analyze the spatiotemporal characteristics of the dynamic water pressure on acting plane gates in comparison with model test results to verify the feasibility of the numerical simulation method. Chen, Y. [24] calculated pulsating water pressure with an error of only 3% via theoretical calculation. Liu, Z. [25] simulated the fluid–structure interaction characteristics of a plane gate with varying opening degrees determined the vibration characteristics. Li, L. [26] studied the hydrodynamic characteristics of an automatic drum gate based on numerical simulation and model testing, as well as the gate pulsation pressure distribution and its pulsation characteristics, under different working conditions. Liu, J. [27] an Wang, J. [28] used numerical simulation to obtain high-confidence hydraulic characteristic results. In previous gate flow-induced vibration research, some scholars used the one-way fluid–structure coupling numerical simulation method to study the flow-induced vibration characteristics during gate operation. However, fluid–structure coupling analysis, the parameters of the flow field and the fact that the structure field are to be solved by a set of equations, make it difficult to obtain a solution. Therefore, the strategy of simplifying the model is adopted to make the numerical analysis results converge, and an oversimplified model reduces the accuracy of the results to a certain extent. With the maturity of hydrodynamic load numerical simulation technology, the flow field numerical simulation method be used to accurately analyze the gate hydrodynamic load [29].

In this study, comprehensive research was conducted the actual engineering of the deep-hole plane steel gate. A numerical analytical technique that integrates “hydrodynamic characteristic computation, gate dynamic characteristic analysis, and dynamic response analysis” is devised for the flow-induced vibration of gate structures. The first step is to assess the total flow field of the water conservation project. Then, using a high-precision numerical simulation method for the flow field, high-confidence hydrodynamic load characteristics operating on the plane gate structure are discovered. The dynamic characteristics of the gate structure in water are calculated using the additional mass method, and the natural vibration frequencies and mode shapes of the dry/wet modes of the gate are obtained to study the influence of the natural vibration characteristics of the structure. Secondly, the dynamic characteristics of the gate itself are numerically simulated and analyzed. Finally, the numerical simulation of structural transient dynamics is used to perform the dynamic response analysis of the flow-induced vibration of the gate structure, and the flow-induced vibration characteristics of the gate, such as dynamic stress and dynamic displacement, are investigated. Compared with the model tested with the numerical simulation method, the method proposed in this study has the advantage of fast speed and little difference in accuracy. It provides some theoretical basis for the feasibility study of the operation of the deep-hole plane gate under the partial opening condition.

2. Numerical Analysis Theory

2.1. Flow Field and Turbulence Model

To meet the demands of calculation precision and freedom. The time-averaged approach of solving the Reynolds equation was chosen in this paper to investigate the flow field. The finite volume method was used to discretize the governing equations of the flow field. The time-averaged approach was used to represent the turbulent flow, but the fundamental equations of fluid mechanics applied to closed laminar flow, therefore a new equation had to be introduced to solve it. To more accurately replicate the turbulent flow, the eddy-viscous model was added. The flow field around the gate discharge could be considered as the turbulent flow of incompressible fluid. The actual flow was intricate and
irregular. When boundary conditions are constant, flow parameters such as velocity can alter at will. Various techniques for numerical simulation analysis and turbulent flow calculation were available at the time. The Reynolds average method’s RNG \( k-\varepsilon \) two-equation calculation model is currently the most used in the engineering field [30–32]. The unstable flow with a significant pressure gradient was responsible for the significantly changing curvature of the streamline at the bottom edge of the gate. The RNG \( k-\varepsilon \) model improved the simulation of the dissipation rate equation, bringing it closer to the actual flow field characteristics of the discharge around the gate area by adding a parameter to reflect the time-averaged rate of change of the flow and taking into account the effect of separation flow and vortex effect on the water. Consequently, using the RNG \( k-\varepsilon \) model will allow for a more precise analysis of the hydrodynamic properties of the gate.

The two equations of the RNG \( k-\varepsilon \) model are as follows.

**\( k \) equation:**
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \sigma_k \mu_{eff} \frac{\partial k}{\partial x_j} \right] - \rho \varepsilon + G_k, \tag{1}
\]

**\( \varepsilon \) equation:**
\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \sigma_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right] - \rho C_2 \frac{\varepsilon^2}{k} + C_1 \frac{\varepsilon}{k} G_k, \tag{2}
\]

and:
\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \tag{3}
\]
\[
G_k = \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j}, \tag{4}
\]
\[
C_2^* = C_2 + \frac{C_v \eta^3 (1 - \eta / \eta_0)}{1 + \beta \eta^4}, \tag{5}
\]

where \( \rho \) is density; \( k \) is turbulent kinetic energy; \( \varepsilon \) is turbulent dissipation rate; \( u_i \) and \( x_i \) are flow velocity and coordinate direction components, respectively; \( \eta \) is stress rate; \( C_\mu, \sigma_k, \sigma_\varepsilon, C_1, C_2 \) are the constants. According to reference [31], the following quantities should be used: \( C_\mu = 0.0845, \sigma_k = \sigma_\varepsilon = 1.39, C_1 = 1.42, C_2 = 1.68; G_k \) is the pressure generation term; \( \mu_{eff} \) is the turbulent effective viscosity coefficient, which takes different values for different Reynolds numbers.

### 2.2. Volume of Fluid

The water and airflow through the gate discharge process was a typical stratified two-phase flow. The mixing of water and air that would take place as the high-speed discharge flow traveling through the bottom edge of the gate was also a crucial characterization of the intricate variations in the hydrodynamic load of the gate [23]. The complexity of water–air mixing had an impact on the hydrodynamic properties of the gate. The process of water and air exchange in the gate’s overflow area needs to be numerically analyzed. The free surface was identified by resolving the volume function of the aqueous phase in the water cell. This method’s benefit was that it required little calculation and was straightforward to implement. The continuity equation of the VOF model [33] is:

\[
\frac{\partial \alpha_w}{\partial t} + u_i \frac{\partial \alpha_w}{\partial x_i} = 0, \tag{6}
\]

where \( \alpha_w \) is the volume fraction of water; \( t \) is the time.

After the introduction of the VOF model into the RNG \( k-\varepsilon \) model, the density \( \rho \) and the viscosity coefficient \( \mu_t \) in the calculation have changed accordingly.

\[
\rho = \alpha_w \rho_w + (1 - \alpha_w) \rho_\alpha, \tag{7}
\]
µ = α_w µ_w + (1 − α_w) µ_a. \hspace{1cm} (8)

2.3. Structural Dynamic Response Analysis

Transient dynamic computation is used in the dynamic response analysis of the gate structure. The motion equation of the transient dynamic structural was calculated in the transient dynamic calculations using the Newmark approach in the implicit algorithm and the direct integration method for the transient dynamic analysis.

\[ [M] \ddot{u} + [C] \dot{u} + [K] u = F(t), \] \hspace{1cm} (9)

where \([M]\) is the mass matrix of the structure; \([C]\) is the damping matrix of the structure; \([K]\) is the stiffness matrix of the structure; \([u]\) is the nodal displacement vector; \([F(t)]\) is the nodal load vector.

The primary goal of the modal analysis was to examine the gate’s inborn dynamic properties. The motion equation for the gate structure system could be reduced to the following when the effect of the water was ignored:

\[ \left( [K] - \omega^2 [M] \right) \phi = \{0\}, \] \hspace{1cm} (10)

where \(\omega\) is the natural frequency of the structural system; \(\phi\) is the eigenvector, which is related to the mode of the structural system; the rest of the symbols are the same as above.

The gate structure’s primary functioning environment is water. The impact of the extra water must be taken into account when analyzing the gate’s vibration. Based on Equation (10), the additional water mass matrix \([M_p]\) is included for the model analysis of the gate under wet conditions, and the motion equation of the gate structure taking the effect of the water into account is:

\[ \left( [K] - \omega^2 ([M] + [M_p]) \right) \phi = \{0\}. \] \hspace{1cm} (11)

2.4. Numerical Analysis Method of Gate Flow-Induced Vibration Response

Fundamental CFD–CSD time-domain coupling calculations are used in the numerical analysis process of flow-induced vibration response analysis. The fluid–structure interaction effect on the gate occurs at the interface between the fluid and the solid, which is different from the research on fluid–structure interaction in a porous medium. According to the available research, several scholars have investigated gate flow-induced vibration using the numerical analysis approach of one-way fluid–structure coupling. In the same physical field, the mass, momentum, and energy conservation equations for fluids and solids are solved. The numerical simulation of fluid–structure interaction is prone to non-convergence in the case of big scale and a large number of grids because of the superposition of residuals and other issues in the iterative calculation of partial differential equations. As a result, when calculating are performed in the same system, the model must be shrunk and made simpler, which may lead to significant deviations from the actual flow field. To analyze the hydrodynamic load characteristics acting on the structural coupling surface, a suitable high-precision flow field numerical analysis approach is chosen. Additionally, the structural coupling surface is subjected to time-history hydrodynamic pressure using the interpolation computation approach. Finally, using the established transient structural dynamics numerical analysis approach. The flow-induced vibration response of the gate is calculated using the weak one-dimensional fluid–structure interaction analysis approach, and it is very accurate and computationally efficient.

The specific operational procedure is listed below. The physical model of the structure was first established in the 3D geometric modeling software, followed by the construction of the gate structure model in CATIA, and finally, the external flow field was modeled in ANSYS Workbench for the numerical analysis of the flow-induced vibration of the deep-hole plane gate. To create the finite element model of the flow field, the structure part
was meshed with hypermesh software and the flow field part was meshed with ANSYS meshing module. To determine the time-history pulsing pressure in all directions of the gate, the flow field was first determined. The steady pulsating time domain’s water pressure value was extracted. The whole approach was used to apply the pulsing pressure to the gate structure’s finite element model in ANSYS APDL. The analysis of the flow-induced vibration response was created. The gate structure’s displacement and stress time-history characteristics under the influence of the pulsing pressure are acquired by applying the 30 s dynamic water pressure in the stable stage. The results of the analysis were determined by looking at the moment and location of the maximum displacement and stress. The numerical study of the flow-induced vibration response of the plane gate is shown in Figure 1.

Figure 1. The numerical analysis process of flow-induced vibration response of gate.

3. Engineering Examples and Finite Element Models

3.1. Engineering Overview and Physical Model

A flat fixed-wheel gate that can open and close under normal water level conditions serves as the functional gate for a water conservation project. The size of the outlet is 3 m × 8 m, the size of the gate structure is 4.44 m wide and 9.85 m high, and the beams are arranged at the same height. The gate material is Q345 steel, Poisson’s ratio $\mu = 0.3$, elastic modulus $E = 2.06 \times 10^5$ MPa, density $\rho = 7850$ kg/m$^3$. The engineering design head $H_s$ is 70 m. At the design water level, the maximum discharge volume of the sluice channel is
1488 m$^3$/s, and the average flow rate through the gate is about 30 m/s. The total length of the drainage channel is 241 m, and the maximum drainage volume is 1544 m$^3$/s.

In this study, the analysis of the gate’s hydrodynamic properties, dynamic properties, and dynamic response analysis was carried out. Both the numerical model of the structure and the numerical model of water were established, respectively. The constructed physical model is shown in Figure 2. The gated water flow numerical simulation calculation domain initially generalized the model following the gate’s and the flow channel’s configuration. While reflecting the detailed construction of the gate area geometry in the actual project, appropriate upstream and downstream boundary conditions were selected to ensure that the flow characteristics of the water flow in the gate area were not affected. In the simulation of the fluid domain, besides the panel, the main beam, small beam, side beam, and diaphragm were spread out vertically and horizontally because of the complex spatial structure of the gate. It was difficult to mesh the flow calculation domain after considering the gate entity. Therefore, only the gate’s outer contour is modeled in the shaded fluorescent green area of Figure 2. The downstream inclination angle was 30°, and the bottom edge’s inclination angle was restored to its original state. According to the previous research [12], the water inlet should be 100 m away from the intake reservoir upstream (more than 10 times the orifice) to achieve the required level of computation accuracy. This distance simulates the upstream inflow conditions. The complete physical model of the gate structure and the flow field in the gate area is shown in Figure 2.

Figure 2. Gate geometry model and flow field model.

3.2. Meshing and Boundary Conditions

The physical model was discretized, a finite element model was created, and the flow field and structure grid were constructed separately following the simulation calculation specifications. Due to the properties of the unstructured grid employed to divide the fluid region and the complexity of the flow field. The flow field area close to the plane gate was encrypted at the same time; Figure 3 depicts the encrypted portion of the grid. When the structure field meshed, the gate structure was discretized into 42,019 shell181 shell elements (four-node finite strain shell), 1,452,495 solid45 solid elements (eight-node solid elements), and a total of 303,044 nodes of the spatial structure system. The gate’s panel and beam system were constructed using the shell element, while the gate’s walking wheel was constructed using the solid element. Figure 3 displays the structural field’s meshing result.
Figure 3. Flow field and structural finite element model of gate area.

The structure boundary conditions were simulated and set following the actual state of the project to produce more accurate flow field results and a realistic simulation of the gate slot flow pattern. The pressure inlet and outlet were set to the same atmospheric pressure, and the wall is a non-slip wall. The closed state is the working condition taken into account in the modal finite element analysis of the gate structure. The gate opening transient and the relative opening \( e/H = 0.125, 0.250, \) and \( 0.500 \) (\( e \) is the opening size of the gate with the unit in meters (m); \( H \) is the gate hole mouth height with the unit in meters (m)). The limitation of the closed state was the contact between the bottom edge of the gate leaf and the bottom of the discharge channel, which limited the displacement of the gate in the Y-direction, and the travel wheels on both sides of the gate and the gate slot, which limited the displacement of the gate in the Z-direction. When the door was opened transiently and partially opened, the Z-direction displacement constraint was changed from the bottom edge to the lifting lug, and other direction constraints were the same as the closing state. The constraint boundary criteria for various structural analysis instances are listed in Table 1.

| Working Condition | Constraint |
|-------------------|------------|
| Closed State      | X-direction—the central axis of the gate leaf  
|                   | Y-direction—the contact part between the walking wheel and the gate slot  
|                   | Z-direction—the bottom edge of the gate leaf |
| \( e/H = 0.125, 0.250 \) and \( 0.500 \) | X-direction—the central axis of the gate leaf  
|                   | Y-direction—the contact part between the walking wheel and the gate slot  
|                   | Z-direction—at the lifting lug |

4. Results and Discussion

4.1. Analysis of the Hydrodynamic Load Characteristics of the Gate

For fluid–structure coupling simulation, the relative opening of the gate \( e/H = 0.125, 0.250 \) and \( 0.500 \) were chosen under the assumption of free discharge of head \((H_s = 70 \text{ m})\), and the pulsating pressure gaining time was 50 s. The dynamic water pressure on the upstream face, gate bottom and downstream face of the gate was measured and recorded. The hydrodynamic pressure on the upstream face of the gate with relative opening \( e/H = 0.250 \) is shown in a time-history figure in Figure 4a. A time-history diagram of the hydrodynamic pressure at the gate’s bottom edge of the gate with a relative opening \( e/H = 0.250 \) is shown in Figure 4b. The water flow is in a relatively turbulent state, and the hydrodynamic pressure in all directions of the gate fluctuates significantly in the region of 0–10 s, according to the hydrodynamic pressure time-history diagram of the gate. After ten seconds, the water flow’s pulsation progressively stabilized and now essentially varies within a range. The major pressure emerges in the dynamic water pressure on the upstream
surface of the gate, and the value after stabilization was above the order of $10^7$ N, according to the time-average size of the pulsing pressure values in all directions under each working state. In the discharge state, the dynamic water pressure close to the gate wall fluctuates, and after a predetermined amount of time, transitions into a stable fluctuation stage.

Figure 4. $e/H = 0.250$ hydrodynamic pressure and frequency spectrum. (a) Time-history diagram of the hydrodynamic pressure on the upstream face of the gate; (b) time-history diagram of the hydrodynamic pressure at the bottom edge of the gate; (c) the spectrum analysis diagram of the stable section of the upstream face hydrodynamic pressure; (d) the spectrum analysis diagram of the stable section of the bottom edge hydrodynamic pressure.

The stable section of the upstream hydrodynamic pressure at $e/H = 0.250$ is shown in the spectrum analysis diagram in Figure 4c. The stable section of the bottom edge hydrodynamic pressure at $e/H = 0.250$ is shown in the spectrum analysis diagram in Figure 4d of the paper. Under the local opening condition, the primary frequencies of the hydrodynamic pressure in all directions are distributed below 1 Hz, and the frequency of the hydrodynamic load was mostly concentrated below 5 Hz.

4.2. Analysis of Gate Natural Vibration Characteristics

The modal analysis of the plane gate was performed using the large-scale finite element analysis program ANSYS Workbench. In the modeling section, restrictions for structural analysis were provided. Under different working conditions, the dry/wet modal features of the gate structure’s structural dynamic properties in air and water were investigated. The structure’s inherent frequency and mode shape were obtained, respectively. The gate structure modal analysis took place with the gate closed, open, and partially open. Figure 5 depicts the form of the gate structure’s first-order dry mode vibration. When the maximal deformation is 1, the legend displays the overall structure’s deformation.
Figure 5. The first-order mode shape of dry mode (opened transiently).

Figure 6 shows the gate structure’s dry/wet modes’ first-order natural vibration frequency and frequency reduction ratio under various working conditions with the normal water level. Except for the closed condition the first-order natural frequency of the dry mode of the gate did not change with the opening degree. Additionally, as the opening degree grew, the wet mode’s first-order natural frequency also somewhat increased. The natural vibration frequency of the gate structure in the wet mode was decreased by 48.01%~56.49% compared to the dry mode, with a very high reduction ratio. It demonstrated how clearly water affects the gate structure’s vibration mode. The impact of the water body in front of the gate cannot be disregarded while analyzing of the natural vibration characteristics of the gate. In all operational states other than closed, the gate’s dry mode vibration shape was the same; precisely, the gate as a whole vibrates horizontally perpendicular to the direction of the water flow, with the largest vibration amplitude at the bottom of the gate. The elastic bending vibration of the middle and lower portions of the gate in the direction of water flow was the wet mode shape of the gate structure. The largest vibration amplitude was found near the gate’s bottom edge. With the dry mode, the position of the maximum vibration amplitude remained constant. However, as opposed to the dry mode’s horizontal vibration, this mode largely vibrated in a bending direction. When the gate is partial opened, the bottom edge of the gate is no longer constrained to move vertically. The mode shape was compatible with the structure’s natural vibration frequency when the gate was closed. It was clear that the vertical (z-direction) constraint on the gate’s vibration characteristics in the wet mode were minimal. From the aforementioned, it was clear that the dominating frequency of the gate pulsing pressure was approximately 1 Hz, which was substantially lower than the gate’s first-order natural vibration frequency under various situations. As a result, the theoretical resonance of the plane gate was practically impossible [34].

Figure 6. Comparison of natural vibration frequencies of first-order dry/wet modes.
The decreasing ratio of the natural vibration frequencies of the wet mode under the relative opening of the gate $e/H = 0.125$ is shown in Figure 7, along with the first four-order natural vibration frequencies of the dry/wet modes. Table 2 displays the dry/wet mode shape characteristics for the relative gate opening of the gate $e/H = 0.125$. With an increase in modal order, the dry mode frequency of the gate appeared to grow, and each order’s mode shape appeared to change. With the rise in the order, the natural frequency of the gate in the wet mode was not noticeable, and the mode shape was mostly the bending vibration of various sections. The first three-order frequencies are gradually increased by the influence of the water.

![Figure 7. Comparison of the first 4 order natural frequencies of the dry/wet modes under the relative opening $e/H = 0.125$.](image)

| Modal Order | Dry Modal Vibration Characteristics | Wet Modal Vibration Characteristics |
|-------------|------------------------------------|-----------------------------------|
| 1           | The gate is bent to the right as a whole | The middle and lower parts of the gate are bent in the direction of the water flow (the bottom edge has the largest amplitude) |
| 2           | Vibration at the lifting ears | The middle and lower parts of the gate are bent in the direction of the water flow (the panel between the middle beams has the largest amplitude) |
| 3           | Waveform vibration of the gate along the direction of water flow | The middle and upper parts of the gate are bent in the direction of the water flow (the local panel has the largest amplitude) |
| 4           | Vibration at the flange of the main girder in the middle of the gate | Bending vibration of beam web grid, longitudinal diaphragm grid, panel grid, and other components |

4.3. Flow-Induced Vibration Response

The flow-induced vibration response study of the gate was subsequently performed based on the hydrodynamic load and modal analysis of the gate. The hydrodynamic load value of the hydrodynamic pressure result of 10 s to 40 s was chosen for the transient dynamic analysis of the gate using the complete approach. The downstream of the gate, the bottom of the gate, and the upstream of the gate all received the hydrodynamic pressure from the three faces, respectively. The analysis used 300 load stages, each of which took 0.1 s to complete.

4.3.1. Flow-Induced Vibration Displacement Analysis

After performing a dynamic response analysis on the gate structure, displacement curves of the nodes corresponding to the maximum displacement in each direction of the gate with various openings throughout the 30 s were obtained. The time-history curve of the greatest displacement in the Y-direction with the relative gate opening of the gate
e/H = 0.250 is shown in Figure 8. It could be concluded that under the condition of relative opening e/H = 0.250, the maximum displacement value of the gate structure in Y-direction appeared at 12.4 s, the displacement value is 2.74 mm, and the maximum displacement value of the overall deformation is 2.74 mm at this time. The displacement curve showed that the gate’s vibration displacement was gradually reduced, which also decreased the likelihood that the gate would malfunction as a result of excessive movement. The highest dynamic displacement of the gate occurs in the direction of the water flow, and the overall deformation was primarily in this direction, according to the available study [16], the gate’s deformation diagram, and the deformation values in each direction. To assess the timing of additional openings’ Y-direction displacement as well as the location of the highest displacement, the same procedure is employed. The dangerous part is the maximum displacement. The total deformation diagram of gate relative opening at e/H = 0.125 is shown in Figure 9. The illustration shows that the connection between the gate leaf in the bottom section and the gate leaf in the middle section is where the gate structure experiences its greatest displacement.

Figure 8. The displacement curve of the node corresponding to the maximum displacement value in the Y-direction when the relative opening of the gate is e/H = 0.250.

Figure 9. Overall deformation diagram of gate relative opening e/H = 0.125 (units: mm).

Table 3 and Figure 10 display the dynamic displacement of each gate component, and these figures also list the maximum displacement opening conditions for the gate as well as the position of the primary component displacement. The center and bottom portions of the gate saw the greatest displacement, and these areas were also where the gate structure was subjected to the greatest water pressure. On the panel of the gate, the displacement
was at its greatest. The comparison of the major component’s maximum displacement values under each opening is shown in Figure 10. The panel displacement, longitudinal web displacement, main beam displacement, side beam displacement, and walking wheel displacement together make up the gate structure’s maximum displacement value. With an increase in the relative opening of the gate, the displacement value of each part of the gate decreased. The primary factor was that, as the gate’s opening increased, both the force acting on it and the area of the gate in contact with the water reduced. The link between the middle section gate leaf and the bottom section gate leaf, which was the weak point of the gate construction during the partial opening operation, is where the gate experienced its greatest displacement under the partial opening operation conditions. The strength design of this location should receive extra consideration in the design.

**Table 3.** Summary table of displacement of important parts of plane steel gate under different opening degrees.

| e/H | Characteristic                        | Component                       | Panel     | Main Beam | Side Beam | Longitudinal Web | Walking Wheel |
|-----|--------------------------------------|----------------------------------|-----------|-----------|-----------|------------------|---------------|
| 0.125 | Displacement value (mm)              | 0.02~3.43                        | 0.01~2.81 | 0.01~1.24 | 0.12~2.83 | 0.01~1.24        |
|      | The location of the maximum value    | The middle of a panel web connecting the bottom segment with the middle segment | The mid-span rear flange of the 3# main beam of the bottom gate leaf | The rear flange connecting the side beam to the 3# main beam | The connection between the bottom section and the middle section web | 2# walking wheel |
| 0.250 | Displacement value (mm)              | 0.09~2.74                        | 0.01~2.09 | 0.01~0.99 | 1.04~2.20 | 0.01~0.77        |
|      | The location of the maximum value    | The middle of a panel web connecting the bottom segment with the middle segment | The mid-span rear flange of the 3# main beam of the bottom gate leaf | The rear flange connecting the side beam to the 3# main beam | The connection between the bottom section and the middle section web | 2# walking wheel |
| 0.500 | Displacement value (mm)              | 0~2.56                           | 0~1.95    | 0~0.91    | 0.04~2.05 | 0~0.69           |
|      | The location of the maximum value    | The middle of a panel web connecting the bottom segment with the middle segment | The mid-span rear flange of the 4# main beam of the bottom gate leaf | The rear flange connecting the side beam to the 4# main beam | The connection between the bottom section and the middle section web | 2# walking wheel |

**4.3.2. Stress Analysis of Flow-Induced Vibration**

Table 4 displays the site of highest stress as well as the maximum equivalent stress of the gate’s key components under a typical 70 m head. Figure 11 shows the highest stress experienced by the gate’s primary components during each opening. The chart shows that each significant component’s stress was within the range of permitted stress when each component of the gate was opened to different degrees. The gate complies with the design specification’s requirements. The regulations of the “Code for Design of Steel Gates in Water Conservancy and Hydropower Engineering” (SL 74-2019) and the “Standard for Scrapping Metal Structures in Water Conservancy and Hydropower Engineering” (SL 226-98). The People’s Republic of China’s water conservancy business adheres to the two standards mentioned above. The precise values are presented in Table 4 together with the actual component materials and gate construction dimensions. The main beam
experienced the most stress, which was followed by the stress on the panel. The primary force-bearing element of the gate was the main beam, and the maximum equivalent stress value 161 MPa occurred at a relative opening $e/H = 0.125$. This was in agreement with the findings of the prior analysis’s first-order mode analysis at the beam’s mid-span rear flange. The middle and bottom portions of the gate were where the gate’s structural stress was mostly focused, and as the degree of openness increased, the maximum value of each component’s equivalent stress was reduced.

![Figure 10. The maximum dynamic displacement of each component.](image)

**Table 4.** Stress summary table of important components of plane steel gate under different opening degrees.

| $e/H$ | Characteristic | Panel | Main Beam | Side Beam | Longitudinal Web | Walking Wheel |
|-------|----------------|-------|-----------|-----------|------------------|---------------|
|       | Equivalent stress (MPa) |       |           |           |                  |               |
| 0.125 | The location of the maximum value | 139   | 161       | 114       | 136              | 119           |
|       | The intersection of the main beam under the gate leaf in the middle section and the upstream face panel |       |           |           |                  |               |
|       | The mid-span rear flange of the #4 main beam of the bottom gate leaf |       |           |           |                  |               |
|       | The transition between thickening section and web near the 3# walking wheel |       |           |           |                  |               |
|       | Bottom gate leaf web |       |           |           |                  |               |
|       | 3# walking wheel and door slot contact |       |           |           |                  |               |
| 0.250 | The location of the maximum value | 113   | 118       | 93.3      | 125              | 95.9          |
|       | The intersection of the 3# main beam of the bottom section gate leaf and the upstream face panel |       |           |           |                  |               |
|       | The mid-span rear flange of the #4 main beam of the bottom gate leaf |       |           |           |                  |               |
|       | The transition between thickening section and web near the 3# walking wheel |       |           |           |                  |               |
|       | Bottom gate leaf web |       |           |           |                  |               |
|       | 3# walking wheel and door slot contact |       |           |           |                  |               |
Table 4. Cont.

| e/H | Characteristic                      | Component                                      |
|-----|-------------------------------------|------------------------------------------------|
|     |                                     | Panel | Main Beam | Side Beam | Longitudinal Web | Walking Wheel |
| 0.500 | Equivalent stress (MPa)              | 103   | 109      | 85.3      | 114            | 85.7          |
|     | The location of the maximum value    |       |          |           |                |               |
|     | The intersection of the 4# main beam of the bottom section gate leaf and the upstream face panel |       |          |           |                |               |
|     | The mid-span rear flange of the 4# main beam of the bottom gate leaf |       |          |           |                |               |
|     | The transition between thickening section and web near the 2# walking wheel |       |          |           |                |               |
|     | Bottom gate leaf web                |       |          |           |                |               |
|     | 2# walking wheel and door slot contact |       |          |           |                |               |
|     | Allowable stress (MPa)               | 192.4 | 196.7    | 192.4     | 196.7          | 1275          |

Figure 11. Maximum dynamic stress diagram of each component.

5. Conclusions

This study uses numerical analysis to examine a real-world project and the flow-induced vibration of a deep-hole plane steel gate. The numerical simulation method of the flow field under the condition of the design head was used to determine the pulsing water pressure acting on the gate. On the foundation, it was also possible to compute the flow-induced vibration response of the gate structure, which served as a guide for the safety assessment study of the partially opened operation condition of the plane steel gate. The conclusions are as follows:

(1) The water body has a considerable impact on the gate’s natural vibration frequency, and the 50% reduction in amplitude is visible. The natural vibration frequency of the gate structure is very different from the dominating frequency of the pulsation which is affecting the hydrodynamic load of the gate. The gate created in this research is less likely to resonate when subjected to hydrodynamic load, according to the various parameters of hydraulic metal structure resonance suggested in the study.

(2) The dynamic displacement results show that each structure of the plane steel gate, when subjected to the conditions of 1/8, 1/4, and 1/2 openings, has dynamic displacement values that all fulfill the specifications, in particular, the requirements for the overall rigidity of the gate. The maximum displacement of the gate appears at the connection between the middle gate leaf and the bottom gate leaf. The size of the dynamic displacement of each component is as follows: displacement of the panel > displacement of the longitudinal web.
displacement of the main beam > displacement of the side beam > displacement of the walking wheel.

(3) The dynamic stress findings show that each component’s stress falls within its permissible stress range, which satisfies the specification’s criteria under various gate structure opening degrees. In this study, the connection between stress and the opening of the gates was found to be inverse. Because the hydrodynamic pressure on the gate gradually diminishes as the gate opens wider, each gate component’s stress gradually decreases. The number 3 main girder of the bottom part of the gate (numbered from bottom to top) and the number 4 main girder of the middle section sustain a larger load, and the corresponding stress of the rear flange of the main girder is heavier, according to the gate stress distribution. The transition area between the bottom section gate leaf and the middle section gate leaf needs to be strengthened to ensure the structural safety.

The high-precision numerical simulation method that is currently in use is the foundation for the numerical simulation method for the dynamic response of the hydraulic plane steel gate described in this research. It has some viability and can serve as a model for safety inspections and hydraulic engineering design.

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