Research on Response Characteristics of Hydraulic Gate Subjected to Non-contact Underwater Explosion Load

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Abstract. In this paper, the response characteristics of deep-hole planar steel gates under the separate induction of bubble pulsating load are studied. Through the large-scale finite element simulation software ABAQUS, using the explicit dynamic finite element analysis method, the contact surface of the gate and the water is taken into account by the fluid-solid coupling algorithm. When the water level is constant, the gate is subjected to explosion and the impact of the generated bubble impact on the gate structure and its anti-explosion ability are analyzed. The equivalent stress, displacement, and equivalent plastic strain of the gate under six different cases were simulated. Then, the effect of bubble pulsating load on the stress characteristics of the gate and the anti-explosion ability of the gate were summarized.

1. Introduction
To prevent man-made deliberate destruction of the dam, the US President signed the Dam Safety and Security Act at the end of 2002 [1]. In the 1990s, Yan and Yan [2] [3], through a lot of research, made a systematic analysis of the dynamic characteristics, vibration characteristics, safety design and evaluation technology of the gate; Xu [4] took the radio gate as the research objects, discussed the reasonable structural layout principles and mechanical calculation models of the gate, and analyzed the stress situation and deformation laws of the different structures of the arc gate. Yin and Chen [5] summarized the research status and trend of underwater explosion from these aspects of theoretical methods, experimental technology and numerical simulation. Zhang, Li [6] used ABAQUS to analyze the plastic deformation and displacement of the hydraulic arc gate in normal conditions under blasting load.

2. Finite element model and calculation cases

2.1. Establishment of the finite element model
The gate designed in this paper is a deep-hole flat fixed-wheel steel gate. The size of contacting area between the gate and water is 6 m×6 m and the width of gate is 1m. The gate is made of Q235 steel material, yield strength [σ] = 235MPa, steel capacity 78.5KN/m³, steel elastic modulus Es=2.07×10¹¹Pa, Poisson’s ratio μ=0.3. The ideal elastic-plastic material is used in the water area (Figure 3). The water density ρ=9.8×10³Kg/m³, the bulk modulus is 2.14×10⁹Pa, and the length of the water area is 5m.

Due to the large number of elements and nodes, some representative elements and nodes were
selected as the monitoring and calculation objects. Figure 1, monitoring node of gate panel (fluid-solid coupling surface): node N1 (30167), node N2 (80402), node N3 (80461), node N4 (128930); Figure 2, monitoring unit of gate panel: unit E1 (18347), unit E2 (55339), unit E3 (79300), unit E4 (79800), unit E5 (131411); Figure 4 is schematic diagram of beam system.

2.2. Calculation cases
This paper discusses six calculation cases under the pulsating load of bubble, when 1kg TNT explosive is located in the middle part of the gate and the bottom of the gate. These are shown in Table 1:

| Case | 1   | 2   | 3   | 4   | 5   | 6   |
|------|-----|-----|-----|-----|-----|-----|
| Explosive position coordinates | (0, 0, -1) | (0, 0, -2) | (0, 0, -3) | (0, -3, -1) | (0, -3, -2) | (0, -3, -3) |

3. Dynamic response analysis of gate

3.1. Equivalent stress analysis of gate
Figure 5 shows the equivalent stress contour of the gate panel structure (fluid-structure coupling surface) under six cases at 0.2ms. By observation, at the same water level, the same time, different locations of blast sources, equivalent stress distribution of the gate panel structure is similar: the local structure of the panel near the blast source is first stressed, then slowly spreads to a larger area, the maximum stress does not appear at the position closest to the blast source, but around the center of the blast source.

Figure 6. Stress curve of the monitoring unit of each cases of the panel

The stress curve of the monitoring unit of each cases of the panel is shown in Figure 6, at the initial stage of explosion, under the same water level, it is found that the panel stress reaches the first peak, the gate is subjected to the maximum stress. Then, the second and the third peak are getting smaller and smaller, indicating that the energy in the bubble is continuously lost, the stress on the gate panel are also be smaller and smaller. After the explosion lasts for a period of time, the stress does not fluctuate much with time, and gradually stabilizes after 0.8s.

3.2. Displacement analysis of gate

In Figure 7, when the explosion takes place in 0.01s, the deformation mainly occurs near the explosion source. After the explosion, the deformation of the gate is more obvious where near the water surface.
Whether the explosion source is in the middle or bottom of the gate, the displacements of the upper and middle parts of the gate panel structure have a great display. The phenomenon shows that the vibration in the upper part of the gate is stronger than that in the bottom.

As shown in Figure 8, the maximum displacement of the gate that appears on the gate panel. The panel absorbs heavy load of the bubble explosion, the displacement of the beam system structure is relatively smaller.

When an explosion occurs, the frequency and impact capacity of the fluid near the water surface are greater than the bottom fluid, and the top of the gate is continuously impacted. The explosion generates a large number of bubbles, and the bubbles are burst near the water surface to release energy, so the displacement near the water surface is large. When the explosion source is located at the bottom of the water, the displacement of the gate beam structure and the panel structure are caused by the explosion impact.

By observing the maximum displacement values of the typical monitoring nodes in the three panels in the case 1 ~ 3 in Figure 9, it is found that as the distance between the explosion source and the gate increases, the displacement at the same time decreases. By observing the Case 2, Case 3, Case 5, and Case 6: the vibration amplitude at node N3 is large and the frequency at node N3 is high. This is caused by the continuous expansion-destruction-contraction-expansion of the bubble. In this state, it cause the whip movement of the gate. It is further shown that under the influence of bubble pulsating load, the gate has both rigid body motion and whip response.
3.3. Equivalent plastic strain Analysis of gate

Observing the four equivalent plastic strain diagrams in Figure 10, it can be found that the plastic strain of unit E4 is larger, and unit E4 is located in the middle of the gate. Observing the unit E5, the peak value is reached immediately when the distance is closer. The maximum plastic deformation at the initial stage, this shows that the gate structure which is located at the bottom of the water has a small extension. Observing unit E4 and unit E5 in the case 1, it can be found that when the gate is damaged by the bubble load, it occurs at the initial stage of the explosion and is instantaneous.
4. Conclusion

From the research, the gate structure damage mainly occurs in the gate panel structure (fluid-solid coupling surface), the stress, the displacement and the plastic strain are mainly in the upper middle part of the panel. For practical reasons, the thickness of the panel should be appropriately thickened. The beam system structure given in this paper is safer and more economical. For the explosion of the bubble to the gate, it is worth noting that the gate's elastic displacement, rigid body motion and the whip response cause the gate to vibrate greatly. To improve the safety of the gate, some new materials can be considered as the following research object.

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