

The Influence of Initiation Position and Depth on Anti-Explosion Safety Performance of Concrete Gravity Dam

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Abstract. Based on AUTODYN finite element software, this paper studies the influence of explosive equivalent and initiation depth on concrete gravity dam, analyzes the changes of internal stress, damage degree, monitoring point speed and displacement of gravity dam under different working conditions, compares the influence of underwater explosion on gravity dam under different working conditions, and provides theoretical reference for structural protection and reinforcement of gravity dam under explosive load.

Keywords: Initiation Position; Initiation Depth; Gravity Dam; Safety Performance.

1. Introduction

Along with the governance of rivers around, large-scale construction of hydroelectric power stations, spatiotemporal scheduling of water resources and optimizing water resources disposition in arid and water-scarce areas, our country has built many hydraulic buildings, which have brought rich social benefits and economic construction returns [1]. Gravity dam is to resist the horizontal water pressure and maintain stability by using the friction force generated by the dead weight in the dam foundation surface and the cohesion between the dam and the foundation, and use the compressive stress caused by the dead weight to offset the tensile stress generated by the water pressure. Because modern war is mainly based on precision missile strike, dam as the main facilities of national economic construction, people's livelihood security and the important pillar of national social stability, will inevitably become one of the primary attack objects of war. Secondly, with the extensive development of underwater engineering, underwater blasting construction is more and more widely used [2], so the research on the anti-blast characteristics of gravity dams has always been a hot issue.

In terms of test technology, Barnes Wallis carried out the first explosion damage test on Mohne dam. He used model test and prototype test to conduct underwater anti-blast performance analysis and found that conventional bombs were difficult to destroy the dam. In 2018, with the help of the dam breach removal project of Feng-man hydropower station, the National Defense Engineering Research Institute carried out the dam dynamic response test under explosion, which provided test support for the subsequent evaluation of high dam anti-blast performance [3]. With the improvement of numerical simulation technology, scholars have conducted a series of studies on underwater explosion and dam anti-explosion by using numerical simulation. Xu Qiang et al. [4-5] took the overflow dam of Huang-deng gravity dam as the research background, considered the high strain rate effect of concrete, carried out numerical simulation on the process of the explosion load acting on the gravity dam, and studied the anti-blast performance of the overflow dam under the contact explosion load. Zhang She-rong et al. [6-8] built a fully coupled model of underwater explosion of gravity dam and analyzed the dynamic response of dam under the impact load of underwater explosion. They found that the head of gravity dam was the weak part of anti-explosion performance. Wang Shuai et al. [9] used AUTODYN to conduct numerical simulation of the process of explosive gravity dam, and the results showed that the underwater veneer explosion caused serious damage to the dam. Li Ben-ping et al. [10] conducted 3D numerical simulation of the whole process of penetration explosion of large-caliber and high-projectile heavy weapons. Liu Jun et al. [11] used LS-DYNA to simulate the dynamic response characteristics of earth-rock dam under explosion load, and the results showed that under the action of explosion load, the propagation law of stress wave was extremely complex, and the mechanical response of earth-rock dam showed remarkable zoning characteristics. Chen Huan et al. [12] studied the dynamic response of continuous rigid frame bridge under explosion load

and obtained the damage accumulation curve of specific element. Zhai Ya-fi [13] et al., based on the example of Koyna gravity dam project, established a multi-coupling simulation model that can reasonably reflect the dynamic damage evolution process of concrete and foundation rock mass of dam body. Ali Noorzad et al. [14] verified the overall strength safety and stability of the dam and found that the elastic-plastic constitutive model was more suitable than other models to safely predict the behavior of CMD. Zhang Jia-wen et al. [15] took gravity dams as the research object, analyzed the dynamic response of the dam when the drilling weapon attacked the dam, and analyzed the damage degree and safety of the dam after the attack.

As a large and important water conservancy facility concerning people's livelihood and social security, gravity dam explosion attack by terrorists will not only cause serious damage to the economic construction facilities in China, but also threaten the personal safety and property safety of the downstream people due to the great harm caused by flood discharge destroyed dam [16]. So, antiknock performance safety problems of large water conservancy project are directly related to people's livelihood security and social stability in our country. Therefore, this paper carried out explosion dam dynamic response under the shock load and reduce the safety protection of underwater shock wave research has very important practical significance.

2. Test Method and Model Establishment

2.1 Finite Element Model

The finite element model is shown in Figure 1. To simplify the model, two-dimensional plane strain is used to establish the finite element model, which consists of gravity dam, water area, explosives, and air. When explosives explode in water, it is necessary to give enough space for water and explosives to flow, so a certain area of air grid is established above the water for the flow of explosives and water. To prevent the detonation wave from reflecting at the boundary, the non-reflecting boundary is defined at the water boundary. Interactions between explosives, water and gravity dams are defined by fluid-structure coupling in AUTODYN. Monitoring points are added to the gravity dam to detect the changes of stress, pressure, velocity, displacement, and other parameters at different positions of the gravity dam.

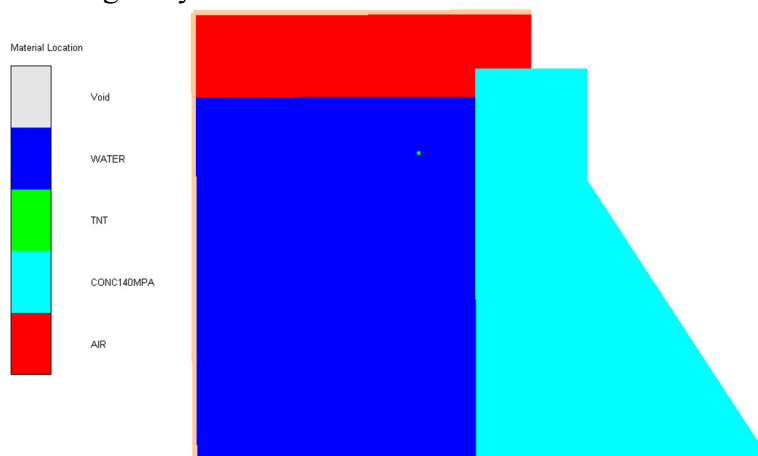


Figure 1. Finite element model

2.2 Material Parameters

The material of the explosive charge in this paper is TNT, and the * MAT_high_explosive-burn constitutive model and the JWL state equation are used. The expression of the JWL state equation is as follows:

$$P = A \left(1 - \frac{w}{R_1 * V} \right) e^{-R_1 V} + B \left(1 - \frac{w}{R_2 * V} \right) e^{-R_2 V} + \frac{we}{V}$$

Where, the detonation product pressure P is a function of relative volume V and internal energy E , where A, B, R_1, R_2 and w are all constants obtained by fitting the cylinder experiment, and the specific parameters are shown in Table 1.

Table 1. TNT material parameter

Material	$\rho/g*cm^{-3}$	$D/m*s^{-1}$	P_{cj}/GPa	A/GPa	B/GPa	R_1	R_2	w
TNT	1.63	6930	21.0	373.7	3.747	4.15	0.9	0.35

Ideal Gas state equation is used for air, and the specific parameters are shown in Table 2.

Table 2. Air material parameter

Material	$\rho/g*cm^{-3}$	Gamma	Reference temperature	Specific heat $/(J/Kg*k)$
Air	0.001225	1.4	288.2	727.6

The linear polynomial equation of state is used for water, and the specific parameters are shown in Table 3.

Table 3. Water material parameter

Material	$\rho/g*cm^{-3}$	A_1/GPa	A_2/Gpa	A_3/Gpa	B_0	B_1	T_1/Gpa
Water	1	2.2	9.54	14.57	0.28	0.28	2.2

RHT constitutive model is used for concrete, and the specific parameters are shown in Table 4.

Table 4. Concrete material parameter

Material	$\rho/g*cm^{-3}$	Shear modulus /GPa	Compression strength/Mpa	Tensile strength/fc	Shear strength/fc
Concrete	2.75	22.6	140	0.1	0.18

2.3 Monitoring Point Setting

Figure 2 shows the setting of different monitoring points. In the numerical simulation calculation, a total of 1-8 measuring points is set, including 5 vertical measuring points near the water side of the gravity dam and 3 horizontal measuring points, which are used to monitor the stress and displacement of the gravity dam body in the explosion process.

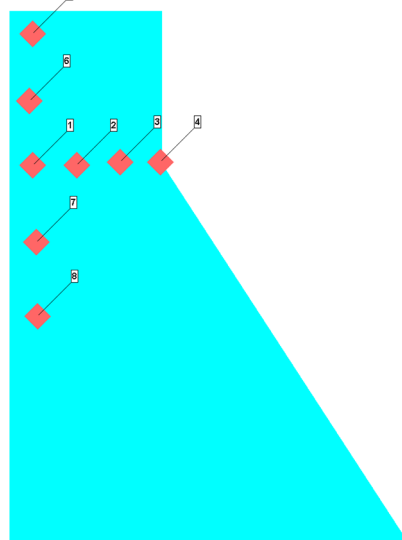


Figure 2. Schematic diagram of monitoring points

3. Results and Analysis

3.1 Action Process of Explosive in Water Explosion

Figure 3 shows the explosion process of 306Kg explosive at an underwater depth of 10m. According to the figure, when the time is 3ms, the shock wave propagates in the water in a spherical manner after the explosive explosion. When the time is 5ms, the shock wave propagates to the gravity dam. When the time is 11ms, the shock wave has acted with the gravity dam, and the shock wave reflects on the surface of the gravity dam. When the time is 5ms~40ms, the shock wave formed by the explosive explosion in water has a continuous effect on the gravity dam, and the shock wave propagates downward along the gravity dam. When the time is 32ms, the shock wave reaches the bottom of the water.

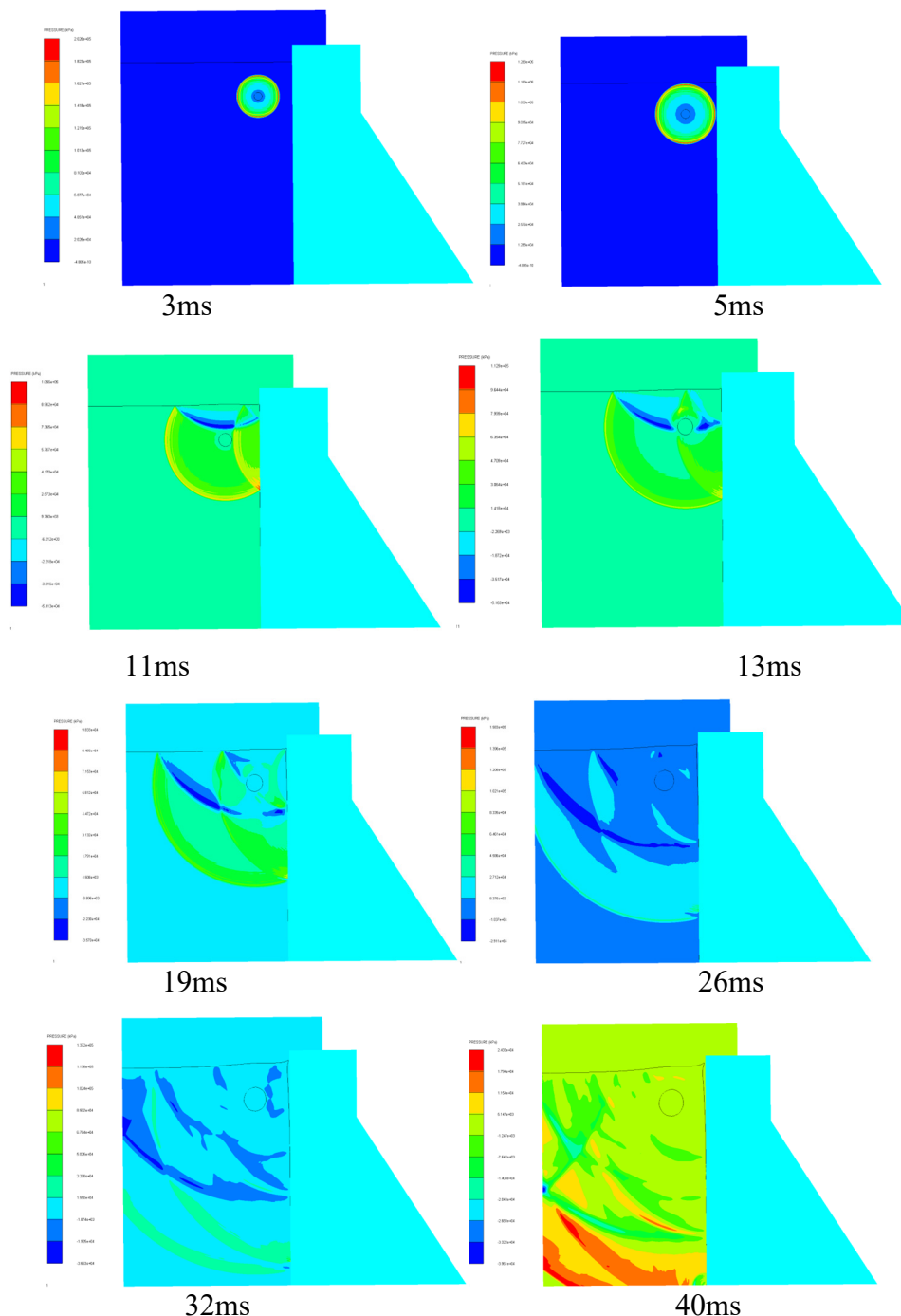


Figure 3. Schematic diagram of explosion process

Figure. 4 shows the change process of gravity dam damage map at different times. When the time is 0-5ms, the surface of the gravity dam is not damaged, because the shock wave did not propagate to the gravity dam before 5ms. When the time is 11ms, the upper end of the gravity dam is damaged. With the increase of time, when the time is 19ms, damage appears in the middle height of gravity dam. During 19~40ms, the damage in the middle height of gravity dam gradually expands. When the time is 40ms, the damage degree of the upper part of the gravity dam is the largest, and the damage degree of the middle part of the dam is also high, indicating that the underwater explosion has a strong destructive effect on the gravity dam.

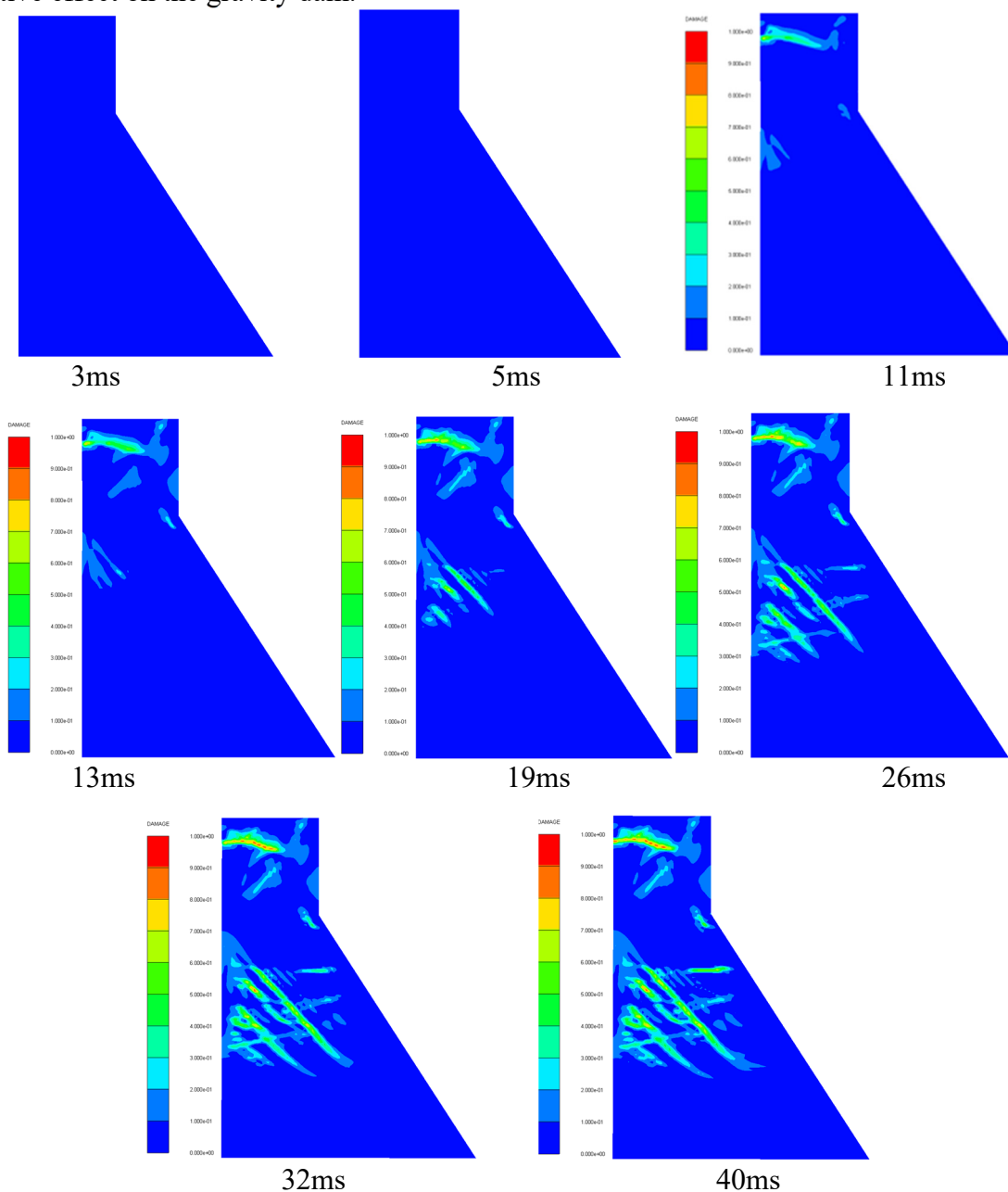


Figure 4. Change process of damage map of gravity dam

Figure. 5(a) shows the stress change curves at different monitoring points. The stress at monitoring points 1-8 reaches the maximum value at 5-10ms and then decreases rapidly. Due to the close distance between monitoring points 1 and 6 and the explosive, the stress at monitoring points 1 and 6 quickly reaches the peak value, which is 120MPa and 94MPa respectively. Figure. 5(b) shows the pressure change curves at different monitoring points. When the gravity dam is subjected to shock wave, the pressure first reaches the maximum value and then rapidly drops to a negative value, indicating that

the monitoring point is subjected to tensile and compressive effects. With the continuous effect of shock wave on the gravity dam, the pressure at the monitoring point fluctuates up and down. Figure. 5(c) shows the curve of velocity measured at different monitoring points over time. In combination with the above, the monitoring points are subjected to stretching and compression, and the velocity of the monitoring points first increases rapidly, and then presents periodic oscillations of up and down velocity. Monitoring shows that the speed of monitoring points 1 and 6 is the largest, which are 12m/s and 8m/s, respectively. Figure. 5(d) shows the displacement curve of different monitoring points over time. It can be found that the displacement of monitoring points 5 and 6 is the largest. This is because the monitoring points 5 and 6 are located near the upper part of the gravity dam, and the width of the gravity dam is narrow, which leads to the large deformation of the gravity dam.

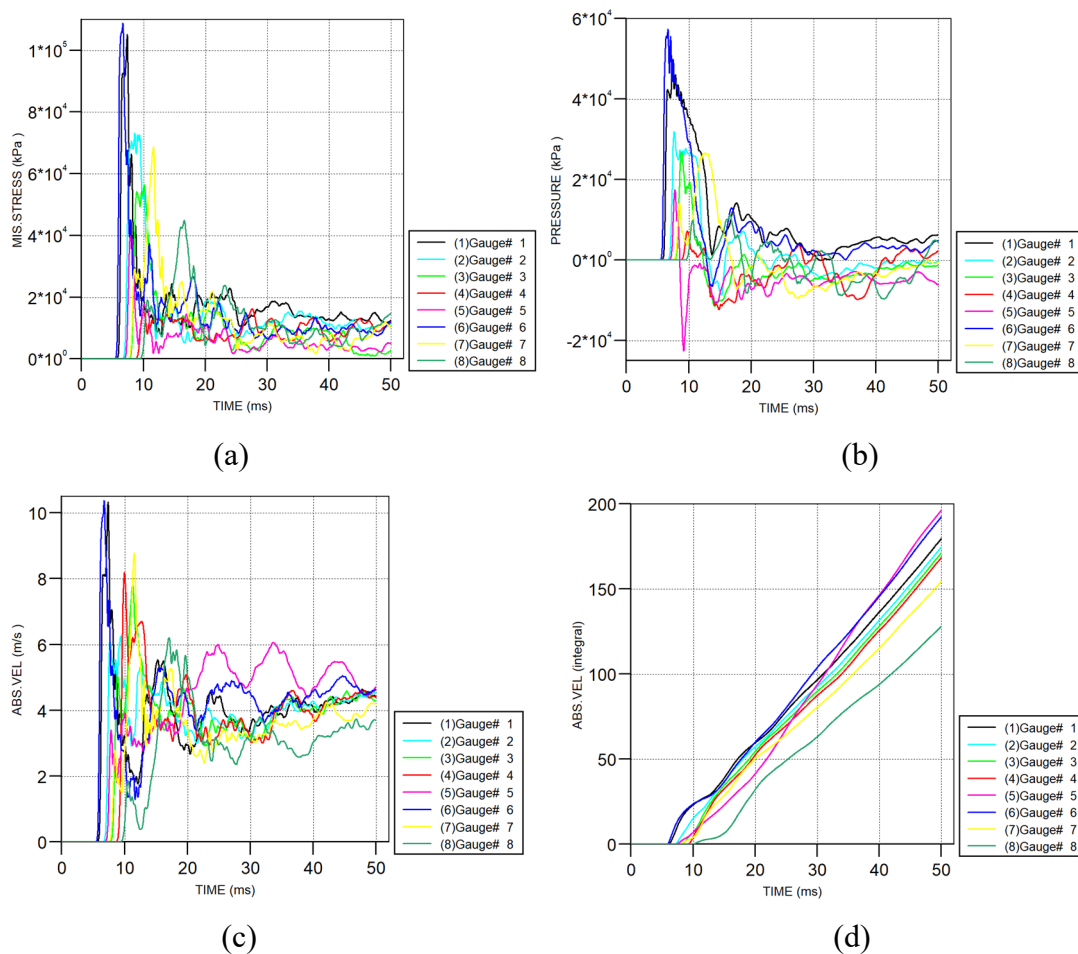


Figure 5. Curve of monitoring points

3.2 Influence of Explosive Equivalent

To study the influence of explosive equivalent on gravity dam, the default depth of explosive is 10m, and the explosive equivalent is set to 125Kg, 306Kg, 500Kg and 750Kg respectively. Then, numerical simulation is carried out, and the calculation time is 50ms.

Figure. 6 shows the damage cloud diagram of gravity dam under different explosive equivalents. It is generally believed that concrete failure occurs when the damage degree reaches 1, that is the concrete cracks occur. Therefore, the area with the damage degree of 1 in the damage map is also the part of concrete crack expansion. It is found that with the increase of the explosive equivalent, the cracks in the gravity dam are more and more, and the cracks are mainly concentrated in the upper part of the dam and the part close to the explosive. When the explosive equivalent is 125Kg, only a few cracks exist in the upper side and middle of the gravity dam. When the explosive equivalent is 306Kg, the cracks in the upper and middle parts of the gravity dam increase obviously. When the explosive

equivalent is 500Kg, the crack increases slightly when the explosive equivalent is 306Kg. When the explosive equivalent is 750Kg, the cracks in the gravity dam increase obviously and the dam is seriously damaged.

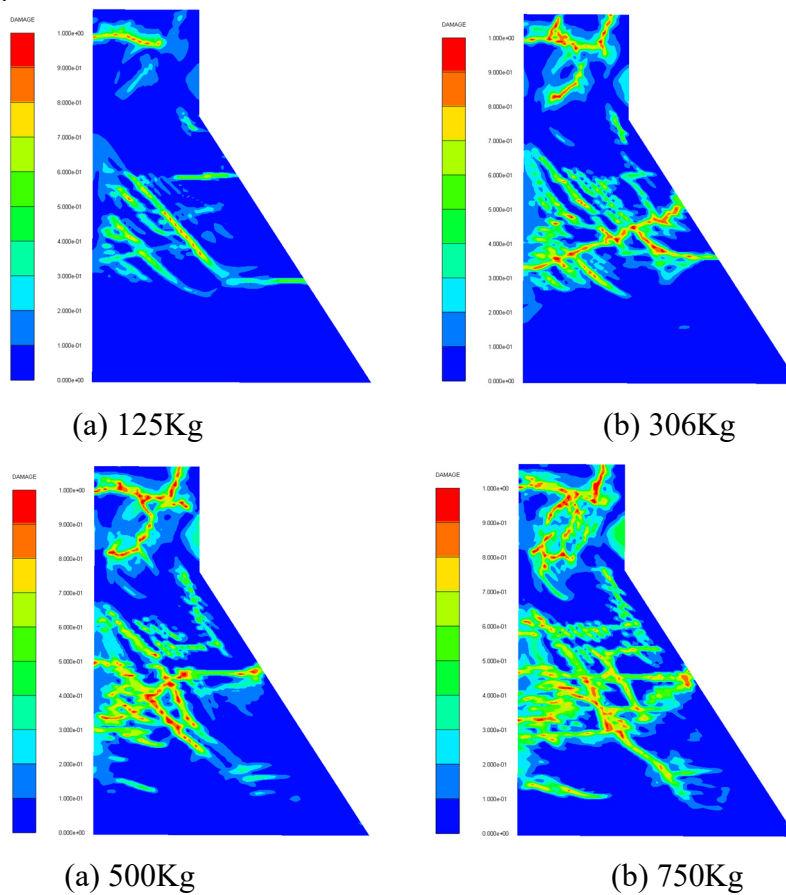
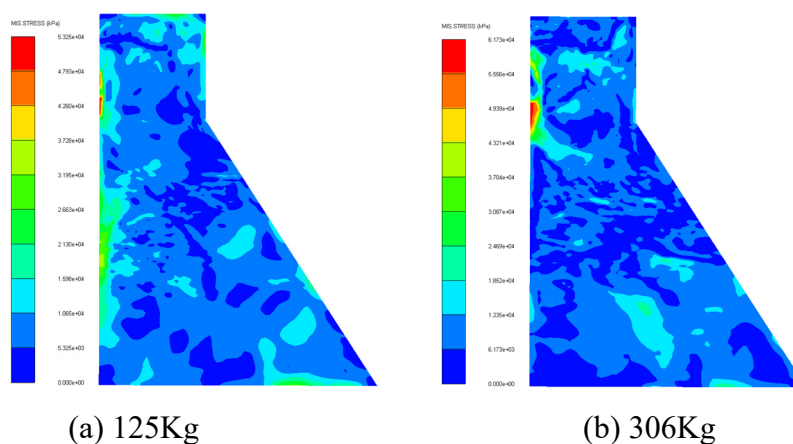


Figure 6. Damage cloud of gravity dam under different explosion equivalents

Figure. 7 shows the stress cloud diagram of gravity dam under different explosive equivalents. When the explosive equivalent increases, the stress value of the gravity dam near the explosive part increases gradually. When the explosive equivalent increases from 125Kg to 7560Kg, the maximum stress value increases from 53.5MPa to 74.0MPa, and the area with higher stress value increases gradually



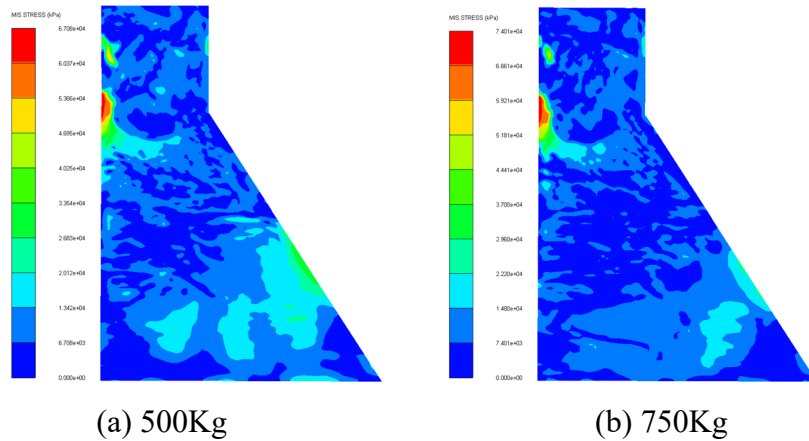


Figure 7. Stress cloud diagram of gravity dam under different explosion equivalents

Figure. 8 shows the velocity change curve of monitoring point 1 with time under different explosive equivalents. With the increase of time, the velocity at monitoring point 1 first increases rapidly and then remain unchanged. When the time is 8ms, the velocity at monitoring point 1 increases rapidly, indicating that the shock wave begins to reach monitoring point 1 at 8ms. With the increase of explosive equivalent, the velocity of monitoring point 1 gradually increases. When the explosive equivalent increases from 125Kg to 750Kg, the maximum velocity of monitoring point 1 increases from 10m/s to 17.5m/s, and the particle velocity caused by explosive equivalent changes greatly.

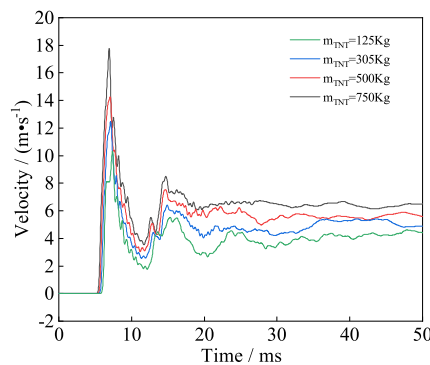


Figure 8. Velocity variation curve of monitoring point 1 with different explosive equivalents with time

Figure. 9 shows the acceleration curve of monitoring point 1 with time for different explosive equivalents. There is little difference in the acceleration of monitoring point 1 under different explosive equivalents. After 15ms, the acceleration value is basically 0, indicating that the basic effect of the shock wave at the monitoring point 1 is finished after 15ms.

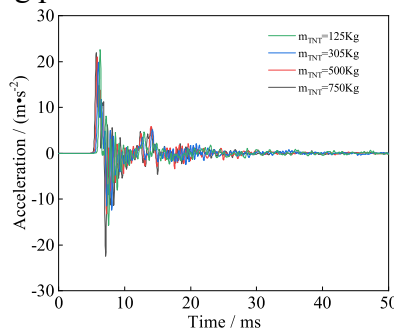


Figure 9. Acceleration curve of monitoring point 1 with different explosive equivalents over time

Figure. 10 shows the time-dependent stress curve of monitoring point 1 under different explosive equivalents. With the increase of explosive equivalent, the stress value of monitoring point 1 gradually increases, mainly reflected in the stress change at 10-20ms with the increase of explosive equivalent.

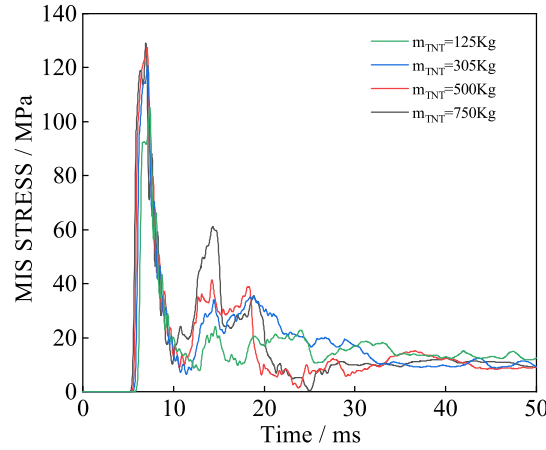


Figure 10. Stress variation curve with time at monitoring point 1 with different explosion equivalents

Figure. 11 shows the displacement curve of monitoring point 1 under different explosive equivalents. With the increase of explosive equivalent, the displacement at monitoring point 1 gradually increases. When the explosive equivalent increases from 125Kg to 750Kg, the displacement increases from 179mm to 328mm.

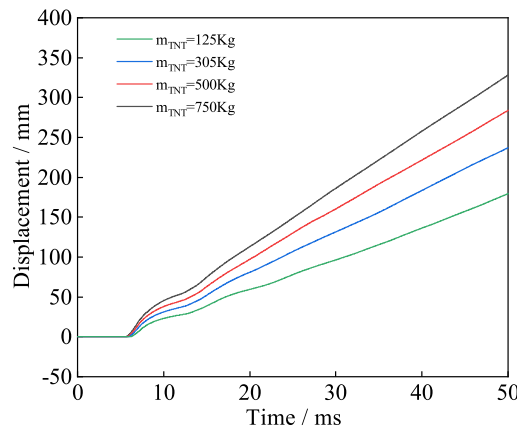


Figure 11. Displacement curve of monitoring point 1 with different explosion equivalent as a function of time

3.3 Influence of Explosive Depth

To study the influence of explosive depth on gravity dam, the explosive equivalent is set as 3065Kg, and the explosive depth is set as 10m, 20m, 30m and 40m respectively. Numerical simulation is carried out and the calculation time is 50ms.

Figure 12 shows the damage cloud diagram of gravity dam under different explosive depths. With the increase of the depth of the explosive, the area of concrete crack concentration gradually approaches the lower end of the gravity dam. When the depth of the explosive is less than 20m, there are many cracks in the slope and vertical part of the gravity dam, which is classified as a relatively dangerous area.

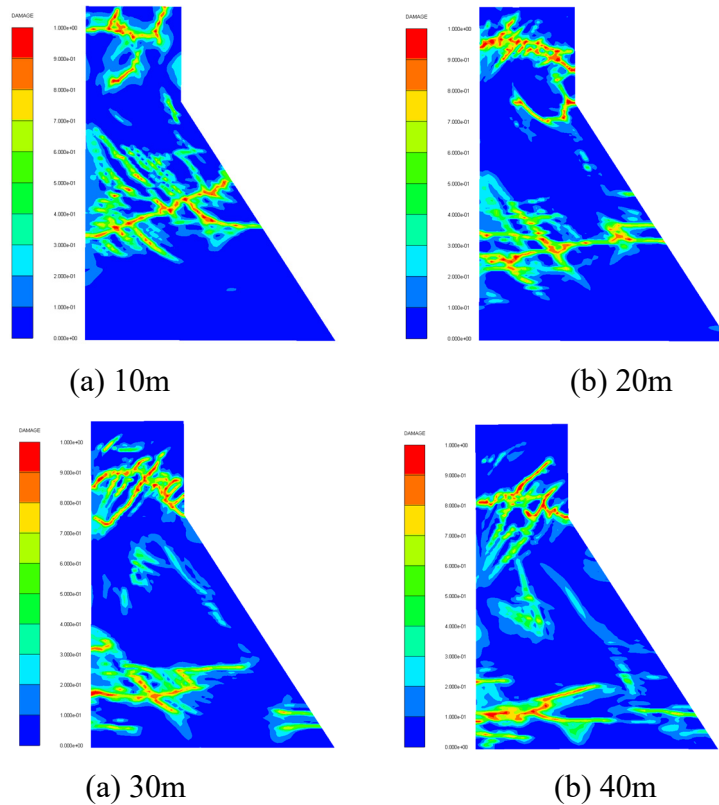


Figure 12. Shows the damage cloud diagram of gravity dam under different explosive depths

Figure. 13 shows the stress cloud diagram of gravity dam at different explosive depths. The maximum stress in gravity dam decreases gradually with the increase of explosive depth. When the depth of the explosive increases from 10m to 40m, the maximum stress in the gravity dam decreases from 41.7MPa to 43.5MPa. The analysis reasons show that, when the depth of the explosive increases, the external pressure on the explosive increases gradually, and the width of the gravity dam at the same height increases gradually, so the bottom of the gravity dam has better anti-blast performance.

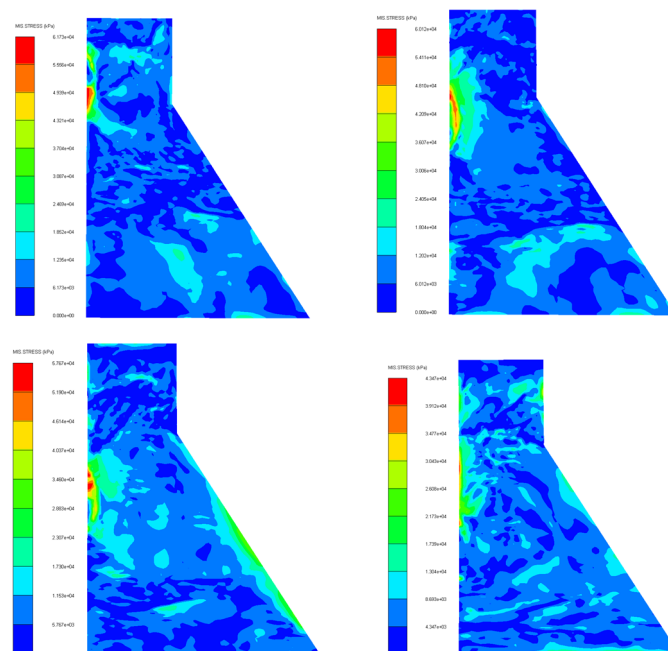


Figure 13. Shows the stress cloud diagram of gravity dam at different explosive depths

Figure 14 shows the velocity variation curve of monitoring point 1 under different explosive depths. With the increase of explosive depth, the velocity at monitoring point 1 gradually decreases. When the depth of the explosive increases from 10m to 20m, the time for the shock wave to reach the monitoring point 1 does not change, and the velocity at the monitoring point 1 decreases slightly. When the depth of the explosive is 40m, the maximum velocity at monitoring point 1 is 9m/s, and the velocity amplitude decreases significantly.

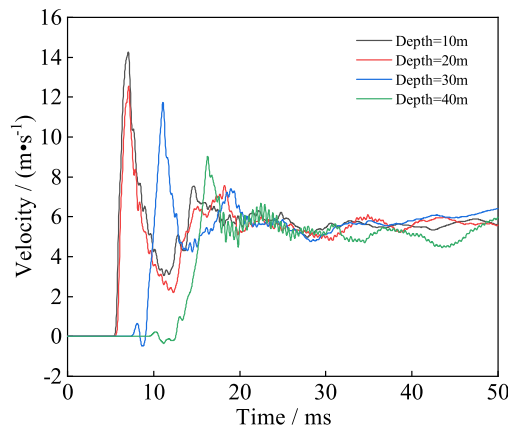


Figure 14. Velocity change curve of monitoring point 1 under different explosive depths

Figure 15 shows the acceleration variation curve of monitoring point 1 under different explosive depths. When the depth of the explosive is between 10m and 20m. The acceleration at monitoring point 1 has a large variation range, which first rapidly increases to 20m/s², then rapidly decreases to -14.8m/s², and basically reaches 0 after 20ms. When the depth of explosive is 40m, the change of acceleration at monitoring point 1 lasts a long time and the value of acceleration is small.

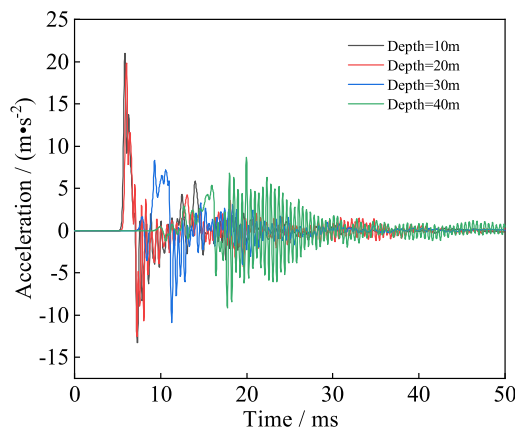


Figure 15. Acceleration curve of monitoring point 1 at different explosive depths

Figure. 16 shows the stress variation curve at monitoring point 1 under different explosive depths. With the increase of explosive depth, the maximum stress at monitoring point 1 gradually decreases, and when the explosive depth is 10m~20m, the difference of stress change at monitoring point 1 is small. When the depth of explosive is 40m, the maximum stress at monitoring point 1 is 72MPa.

Figure. 17 shows the displacement curve of monitoring point 1 under different explosive depths. With the increase of explosive depth, the displacement at monitoring point 1 gradually decreases. When the explosive depth increases from 10m to 40m, the displacement at monitoring point 1 decreases from 284mm to 199mm.

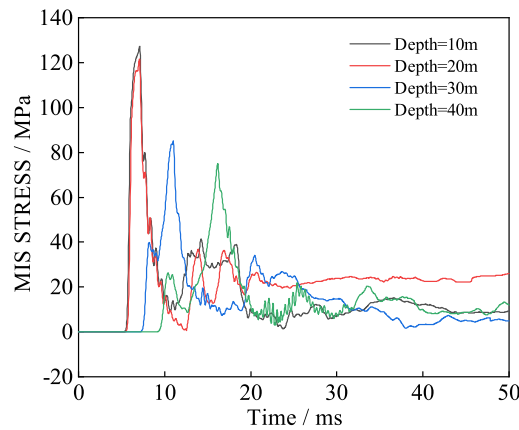


Figure 16. Stress change curve of monitoring point 1 under different explosive depths

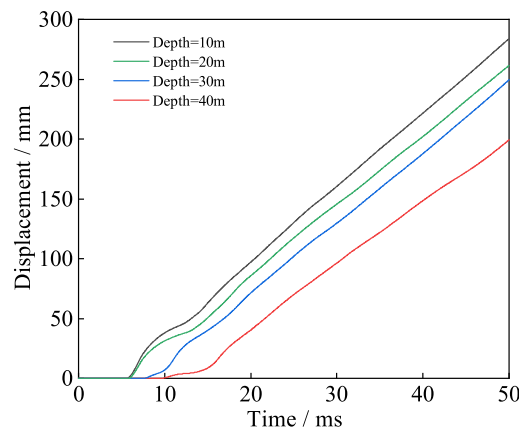


Figure 17. Displacement curve of monitoring point 1 at different explosive depths

4. Conclusion

Based on numerical simulation technique, the influence of specific explosive equivalent and initiation depth on gravity dam is studied. By changing the explosive equivalent to 125Kg, 306Kg, 500Kg, 750Kg, and the explosive depth to 10m, 20m, 30m, 40m, the velocity, acceleration, stress, and displacement results of the gravity dam monitoring points are analyzed. The main conclusions are as follows:

(1) With the increase of the explosive equivalent, the cracks in the gravity dam are more and more, and the cracks are mainly concentrated in the upper part of the gravity dam and the part close to the explosive. When the explosive equivalent is 750Kg and the explosive depth is 10m, the cracks in the gravity dam increase obviously and the gravity dam is seriously damaged.

(2) With the increase of the depth of the explosive, the area where the concrete cracks are concentrated gradually approaches the lower end of the gravity dam. When the explosive equivalent is 306Kg and the depth of the explosive is less than 20m, there are many cracks in the slope and vertical part of the gravity dam, which is classified as a relatively dangerous area.

(3) As a major people's livelihood project, it is suggested to strengthen the gravity dam according to the study of anti-blast performance during the construction, to prevent the occurrence of major safety incidents.

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