The influence of detonation interval on the dynamic response of underground fortification

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Abstract. It is of great theoretical significance and engineering application to investigate the influence of detonation interval on the dynamic response of underground fortification under blasting loading. First, a numerical simulation of underground fortification under blast loading is carried out based on the continuum-discontinuum element method. Then, the displacement characteristic of underground fortification is analyzed. Finally, the fracture characteristic of underground fortification is analyzed. The results indicate that the increasing trend of displacement at the top boundary gradually decays with the increase of detonation interval. The final value of displacement at the left boundary first increases and then decreases with the increase of detonation interval. With the increase in detonation interval, the proportion of concrete undergoing shear fracture at the top, left, and right boundary gradually decreases.

1. Introduction

Underground fortifications refer to the fortifications built below the ground to protect personnel, command posts, military technical equipment, and industrial enterprises. Due to the high concealment and strong protection of underground fortifications, many countries have transferred important military facilities, weapons, and equipment to the ground. Currently, the penetrating projectile is the main weapon to destroy the underground fortifications, and its damage mechanism includes penetration and shock wave. The research on the dynamic mechanical response of underground fortifications under shock wave load is helpful in optimizing the design scheme of underground fortifications and guiding the striking scheme of weapons and equipment [1, 2].

In terms of research on the damage of earth-penetrating weapons to underground fortifications, scholars have carried out much work, summarized the development trend of foreign deep subterranean penetrating bombs, and obtained the corresponding algorithm [3, 5]. Zhu et al. [6] considered the earthquake damage effect of the earth-penetrating bomb on the underground works. The study used the dynamic finite element method to obtain the dynamic response time history of the underground works under the explosion load of the earth-penetrating bomb. Deng et al. [7] analyzed the damaging effect of the tunnel crossing under the nuclear drill ground penetrating explosion. Yang & Deng [8] proposed that although the current conventional weapons have made a qualitative leap, it is still difficult to destroy solid deep underground projects with a single attack. Hence, they considered multiple repeated attacks, but the final damage depth of multiple repeated attacks tends to the limit value. Deng [9] summarized the free field impact calculation formula for repeated strikes. Song et al. [10] conducted corresponding research on the crater effect in different media in underground protection engineering.

Li [11] carried out the three-dimensional numerical simulation of the whole process of the penetration and explosion of large caliber, high explosive, and heavy weapons. The research studied the damaging effect of dam aggregation under the action of multi-point simultaneous strikes against the ground penetrating targets.

For the damaging effect of a single strike on underground fortifications, scholars have made much research. However, in real scenes, multiple subterranean penetrating bombs usually attack underground fortifications cooperatively, and there is a superposition effect of shock waves. Few scholars have studied this process. In this paper, aiming at the working condition type of multiple strikes, the influence of detonation interval on the dynamic mechanical response characteristics of underground fortifications is studied, focusing on the characteristics of displacement evolution and fracture evolution.

2. Numerical simulation

2.1 Continuum-discontinuum element method

The continuum-discontinuum element method (CDEM) is proposed based on the Lagrangian energy system. The dynamic relaxation method is adopted for an explicit iterative solution, which can enhance the ability to solve large deformation and dynamic problems. Based on CDEM numerical method, a lot of scholars investigated the dynamic response of the structure under dynamic loading, and the accuracy of CDEM is verified [12]. Therefore, the dynamic mechanical response of underground fortification under blast loading is simulated by CDEM, and the influence of detonation interval on the dynamic response of underground fortification is analyzed.

2.2 Numerical model

The established numerical model of underground fortification, rock, and explosives is plotted in Figure 1. In order to reduce the computing time of numerical simulation, only the rock mass around the underground fortification and explosives is modeled, and the reflection-free boundary condition is used to eliminate the influence of artificial truncated boundaries (i.e., left boundary, right boundary, and bottom boundary) on the shock wave propagation. For the underground fortification, the burial depth is 50 m, the thickness of the concrete wall is 1.8 m, the horizontal length of the outer boundary is 15 m, and the vertical height is 10 m. Explosives A, B, and C are located at the same horizontal height, with 10 m in sequence. Explosive A is located directly above the underground fortification, with a vertical distance of 15 m. To balance the calculation efficiency and calculation accuracy, the mesh size is 1 m for rock mass, 0.2 m for underground fortification, and 0.05 m for explosive. The JWL equation of state is used to characterize the explosive initiation process. The intrinsic fracture energy model is used to characterize the dynamic fracture process of rock and concrete under the shock wave. The mechanical parameters of explosive, rock mass, and concrete are listed in Tables 1 and 2.

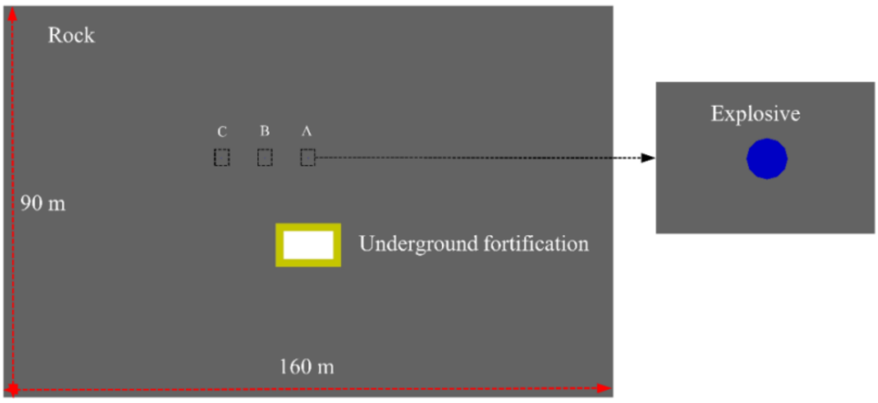


Figure 1. Numerical model of underground fortification, rock, and explosives

Table 1. Mechanical parameters of JWL equation of state

Material	Charge density (kg/m^3)	Initial specific internal energy (J/m^3)	CJ pressure (Pa)	Detonation velocity (m/s)
TNT	1630	7e9	21e9	6930

Table 2. Mechanical parameters of rock mass and concrete

Material	Density (kg/m^3)	Elastic modulus (GPa)	Cohesive strength (MPa)	Tensile strength (MPa)	Friction angle (°)
Concrete	2500	35	18	9	62.5
Rock	2300	10	7	3	40

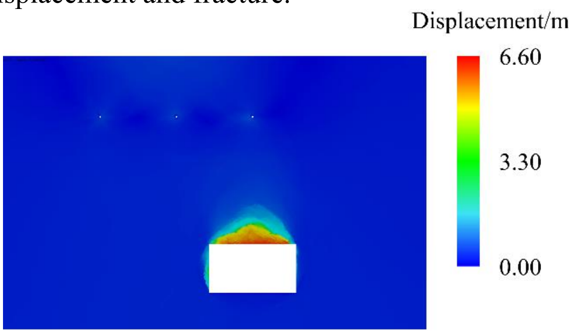
2.3 Numerical result

To investigate the effect of detonation interval on the dynamic mechanical response of underground fortification, numerical simulation with detonation interval t_i = 0.00 s, 0.01 s, 0.02 s, and 0.03 s are conducted. The detonation sequence is defined as Explosive A, Explosive B, and Explosive C. Based on the numerical result, a comparative analysis is conducted for the displacement and fracture evolution characteristics, respectively.

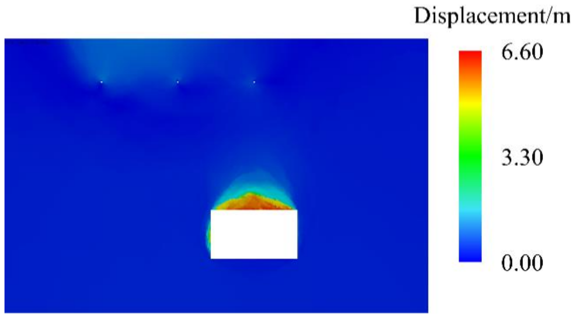
2.3.1 Displacement characteristic

The detonation moment of Explosive A is defined as the initial moment (i.e., t = 0 s), and the resultant displacement nephograms of rock mass and underground fortification at t = 0.5 s are plotted in Figure 2. To facilitate the comparison and analysis, the maximum value of the displacement legend is set to 6.6 m, and the minimum value is 0 m.

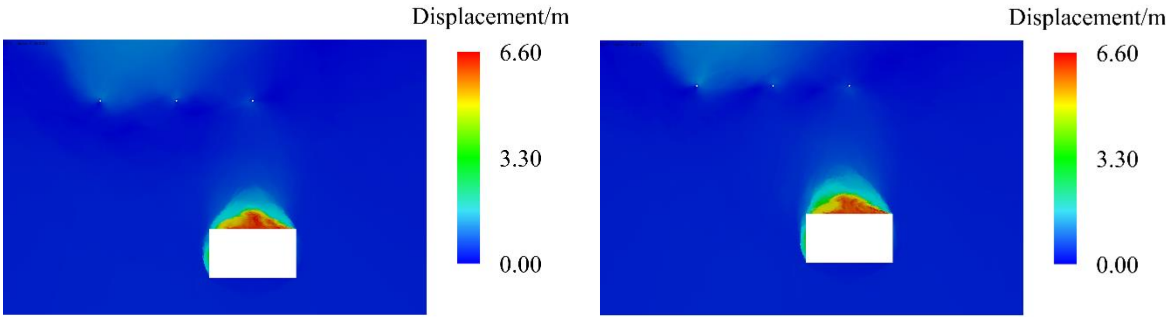
By comparing the displacement nephograms of rock mass near the explosives, it is observed that for the three conditions of t_i = 0.01 s, 0.02 s, and 0.03 s, the larger the detonation interval is, the larger the displacement value of rock mass near the explosives is. This is due to the previous explosion shock wave that has led to displacement and damage to the surrounding rock near the unexploded explosives. Once the explosive explodes, the shock wave is more likely to make the surrounding rock displacement and fracture.



(a) T_i = 0.00 s



(b) T_i = 0.01 s



(c) T_i = 0.02 s (d) T_i = 0.03 s

Figure 2. Displacement nephograms of rock mass and underground fortification

According to the displacement nephograms of underground fortification corresponding to different detonation intervals, it is seen that the region with large displacement is located at the top boundary and the left boundary. This is since these two boundaries are directly subjected to the dynamic action of the shock wave. The displacement value of the top boundary is significantly larger than that of the left boundary. The discontinuous characteristic of displacement indicates that the underground fortification has been ruptured and scattered under the shock waves. By comparing the displacement nephograms of surrounding rock, it is observed that as the detonation interval increases, the region of large displacement of the rock above the underground fortification expands. This is because the previous shock waves have ruptured the concrete and surrounding rock, forming the new rupture surface. The subsequent shock waves more easily cause large displacement of surrounding rock. As the detonation interval increases from 0 s to 0.03 s, the region of concrete undergoing large displacement at the top boundary of the underground fortification gradually moves from the middle part to the right part.

To accurately study the effect of detonation interval on the displacement of underground fortification, the time-history curves of displacement at the middle point of the top and left boundaries are plotted in Figures 3 and 4. For the top boundary, it is observed that the detonation interval does not affect the changing trend of displacement. With the increase of time, the displacement first increases approximately linearly, and then remains constant. In addition, as the detonation interval increases, the increasing trend of displacement gradually decays, and the growth rate in the case of t = 0.02 s and 0.03 s is similar. For the left boundary, it is concluded that the detonation interval does not affect the changing trend of displacement. As time increases, the displacement gradually increases, and then the increasing rate gradually slows down. In addition, with the increase of detonation time, the final value of displacement first increases and then decreases.

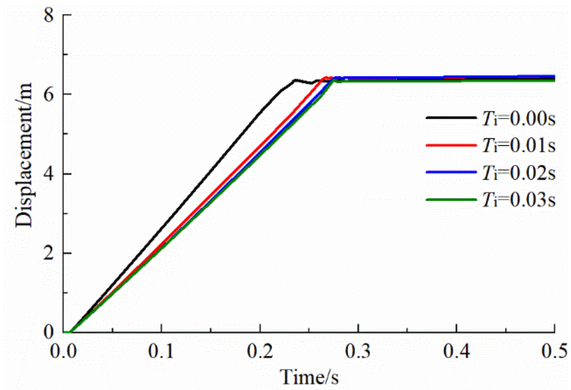


Figure 3. Time-history curve of displacement at the top boundary

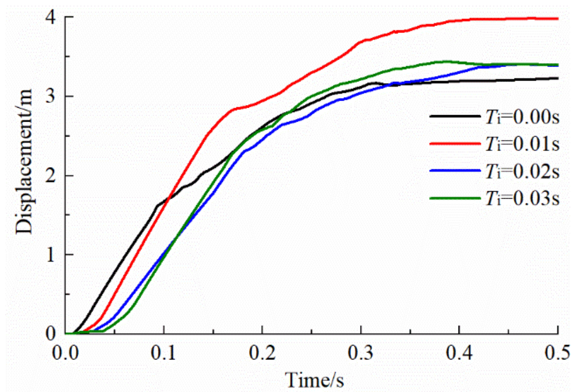


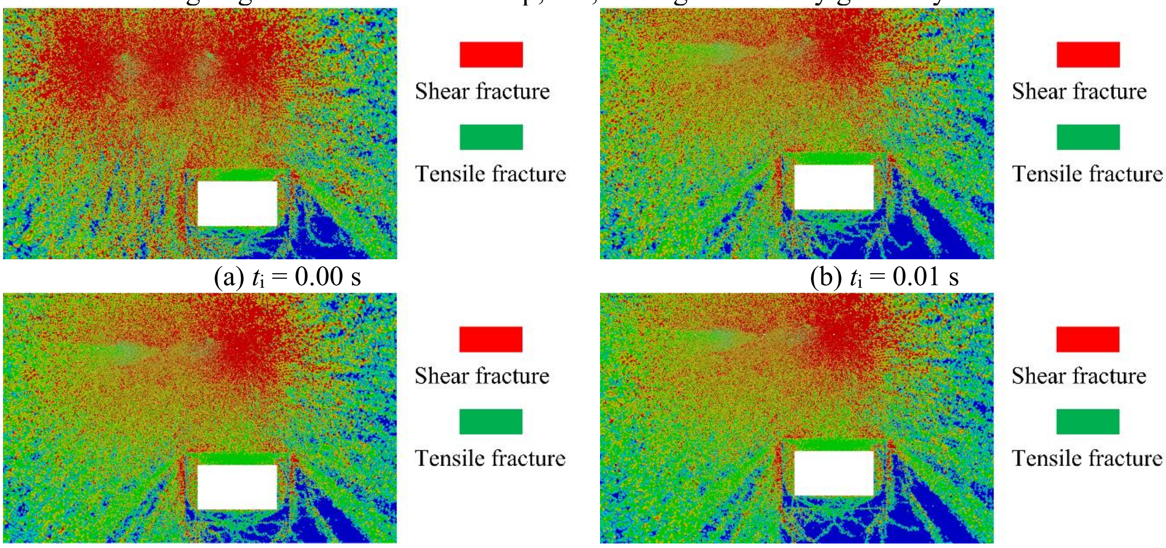
Figure 4. Time-history curve of displacement at the left boundary

2.3.2 Fracture characteristic

The fracture nephograms of rock mass and underground fortification at $t = 0.5$ s are plotted in Figure 5. The shear fracture is indicated by the red line, and the tensile fracture is indicated by the green line. To clearly observe the spatial distribution characteristic of the cracked interface, only the fracture nephogram of surrounding rock near the underground fortification and explosives is plotted.

The rock mass around the explosive mainly undergoes shear fracture when the detonation interval $t_i = 0.00$ s. There are three shear damage clustering regions in Figure 5(a). As the distance from the explosive increases, the proportion of interface undergoing tensile fracture gradually increases. For the case of detonation interval $t_i = 0.01$ s, 0.02 s, and 0.03 s, it is observed that there is only a shear damage clustering region, which is located near Explosive A. The rock mass adjacent to Explosives B and C mainly undergoes tensile fracture, and the proportion of interface undergoing shear fracture gradually increases with the increase of distance. Therefore, it is concluded that the detonation interval influences the fracture type of rock mass around Explosives B and C.

For the underground fortification, it is observed that the fracture characteristics in the four cases are similar. The tensile fracture mainly occurs at the top and bottom boundaries, and the shear fracture mainly occurs at the left and right boundaries. With the increase in detonation interval, the proportion of concrete undergoing shear fracture at the top, left, and right boundary gradually decreases.



(a) $t_i = 0.00$ s (b) $t_i = 0.01$ s

(c) $t_i = 0.02$ s (d) $t_i = 0.03$ s

Figure 5. Fracture nephograms of rock mass and underground fortification

To obtain the fracture evolution characteristic of underground fortification more accurately, the time-history curve of the crack ratio is plotted in Figure 6. The curve has stage characteristics, including a sharp growth stage and a dynamic stability stage. For the case of detonation interval $t_i =$ 0.00 s, the crack ratio increases sharply only once from 0.00 s to 0.2 s, which is due to the shock waves (Explosive A, Explosive B, and Explosive C) arriving almost simultaneously. For the case of detonation interval $t_i = 0.01$ s, 0.02 s, and 0.03 s, the crack ratio increases sharply three times, which is due to the shock waves do not reach the underground fortification simultaneously. In addition, with the increase of detonation interval, the start time of the second sharp increasement and third sharp increasement gradually increases. After $t = 0.2$ s, the concrete at the top boundary reaches the bottom boundary, and some newly cracked planes appear due to the collision between concrete.

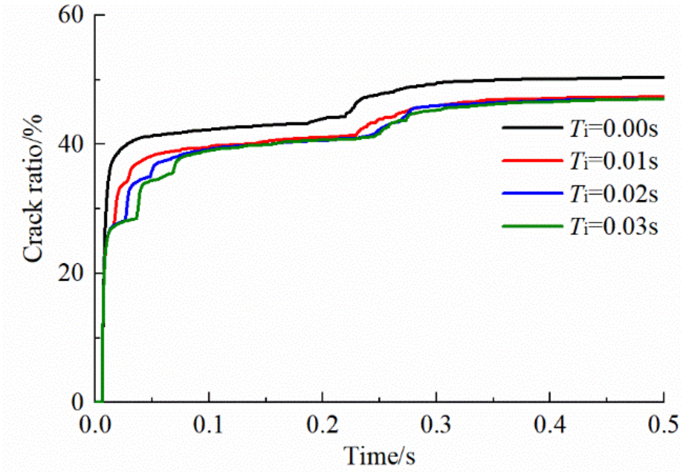


Figure 6. The time-history curve of crack ratio

3 Conclusions

Based on the continuum-discontinuum element method, the influence of detonation interval on the dynamic response of underground fortification is studied. The following conclusions can be drawn:

1) The region with large displacement is located at the top boundary and the left boundary. The increasing trend of displacement at the top boundary gradually decays with the increase of detonation interval. The final value of displacement at the left boundary first increases and then decreases with the increase of detonation interval.

2) With the increase of detonation interval, the fracture type of rock around Explosives B and C changes from shear fracture to tensile fracture. With the increase of detonation interval, the proportion of concrete undergoing shear fracture at the top, left, and right boundary gradually decreases.

This paper quantitatively investigates the effect of detonation interval on the displacement and fracture evolution characteristics of underground fortification, which is of significance to guide the fire strike and improve the design of underground fortification. However, the dynamic response of fortification under blasting load is simulated based on the two-dimensional numerical model in the paper. To investigate the influence of detonation interval more accurately, it is necessary to conduct a full-time numerical simulation of an underground fortification based on the three-dimensional numerical model. It is better to deeply study the superimposed effect of shock waves and the interaction process between rock mass and fortification.

Acknowledgement

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