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Influence of explosion distance on the dynamic mechanical response of underground fortification

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Influence of explosion distance on the dynamic mechanical response of underground fortification

Q D Lin[1], C Feng[2], Y D Gan[1*], P D Cheng[2], W J Jiao[1], Y L Zhang[1] and J F Yuan[1]

[1]Xi'an Modern Chemistry Research Institute, Xi'an, Shaanxi, 710065, China

[2]Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

[*]ganyundan@163.com

Abstract. Many key military targets have been moved underground to improve the battlefield survivability. To study the influence of explosion distance on the dynamic mechanical response of underground fortification, the full-time numerical simulation is conducted based on the CDEM numerical method. First, four numerical simulations corresponding to different explosion distances are conducted. Then, the displacement characteristic of underground fortification and rock mass is analyzed. Finally, the fracture characteristic of underground fortification and rock mass is analyzed. The numerical results show that the damage degree of underground fortification and rock mass weakens with the increase of explosion distance. When the distance increases from 5 m to 20 m, the volume of rock entering the underground fortification decreases from 24.78 m^3 to 0 m^3. The time-history curve of crack ratio has the four-stage characteristic, and it increases rapidly during the explosion initiation process. As the explosion distance increases, the top concrete wall mainly undergoes tensile fracture.

1. Introduction

To improve the battlefield survivability, many important military facilities (e.g., control system, command system) have been moved underground in the modern war. As a commonly used weapon against the underground fortification, the earth-penetrating projectile explodes after drilling to a certain depth, thereby destroying the fortification. It is the best condition to use the earth-penetrating projectile to explode by drilling into the underground fortification through the rock formation.

To improve the strike capability of earth-penetrating projectile and enhance the defense capability of underground fortification, many scholars conducted research on the damage characteristic of underground fortification under the explosion shock wave. Aiming at the dynamic response of underground arch structure under side blast load, Chen, Zhang and Zhou derived the rock-structure interaction controlling equation and time-history curves of displacement, velocity and acceleration based on theoretical analysis. [1-3] Since the dynamic damage process of underground fortification is complex, some assumptions are proposed to simplify the theoretical analysis. To more accurately investigate the damage characteristic of underground fortification under blast load, scholars conducted lots of tests and generalized the damage law of underground fortification. [4-8] During the dynamic damage process of underground fortification, the load distribution law and load coefficient of explosion shock wave play an important role. Based on the theoretical analysis and experimental research, scholars studied the load distribution characteristic on the fortification surface under different working conditions. [9-12]

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With the rapid development of computer technology, many numerical methods are proposed. Due to the low cost and convenience of implementation, scholars studied the dynamic mechanical response of underground fortification under blast load based on numerical simulation. Lagrange method, Euler method and Arbitrary Lagrange-Euler (ALE) method are commonly used simulation methods, and the ALE method combines the advantages of Lagrange method and Euler method. [13-17] To study the correlation between the burst depth and the damage of typical underground constructions, Fan [18] simulated the damage evolution process of concrete fortification when the 14.7 kg explosive were detonated at different depths. Chen [19] simulated the modal and dynamic response of underground arch structure under blast load, and obtained the low order natural frequency variation curve and the dynamic response time-history curve. Masi [20] investigated the response of a curved masonry subjected to blast load, and explored the influence of various micro-mechanical parameters on the overall dynamic structural response of the system. Qian [21] numerically studied the influence of charge weight on blast resistance of the utility tunnel, and investigated the effect of buried depth, reinforcement ratio, shear reinforcement arrangement and wall thickness. Huo [22] numerically simulated the failure process of arched structure with reinforced concrete straight walls, and proposed that the failure mode of structure gradually transitions from spalling failure and bending failure to shear failure.

Although a great amount of research on the damage characteristic of underground fortification under blast load has been done, most of the numerical methods currently used belong to the continuum-based method, which are hard to simulate the transformation of underground fortification and rock from continuous medium to discontinuous medium. To study the influence of explosion distance on the dynamic mechanical response of underground fortification, four numerical simulations corresponding to different explosion distances from 5 m to 20 m are conducted based on the continuum-discontinuum element method. The displacement and fracture characteristics of underground fortification are quantitatively investigated.

2. Numerical simulation

The continuum-discontinuum element method (CDEM) is established based on the Lagrangian energy system. To improve the applicability of solving large deformation problems, the dynamic relaxation method is adopted for explicit iterative solution. As a coupled method, CDEM combines the advantages of continuous simulation and discrete simulation, and it can accurately simulate the whole process of material from continuous deformation to fracture until movement. The basic model is composed of block and interface, and the block and interface is used to represent the continuous features and discontinuous features of material, respectively. [23-26]

Based on CDEM numerical method, many researchers investigate the dynamic mechanical response of material under blast load and impact load, and the experimental results verify the accuracy of CDEM. [27-29] Therefore, the dynamic mechanical response of underground fortification under blast load is simulated by CDEM, and the displacement and fracture characteristics are investigated.

2.1. Numerical model

The numerical model of underground fortification and rock mass under blast load is plotted in figure 1. The horizontal length of underground fortification is 15.0 m, the vertical height of underground fortification is 10.0 m, and the thickness of concrete wall is 1.8 m. The underground fortification is 117.5 m away from the left boundary of rock mass and 70 m away from the bottom boundary of rock mass. The model is meshed by triangular element, considering the model size and computational efficiency, the mesh size of explosive is set to 0.05 m, the mesh size of underground fortification is set to 0.2 m, and the mesh size of rock mass is set to 3.0 m. The JWL equation of state is adopted to simulate the explosive initiation process, and the mechanical parameters are listed in table 1. The mechanical parameters of rock and concrete are listed in table 2.

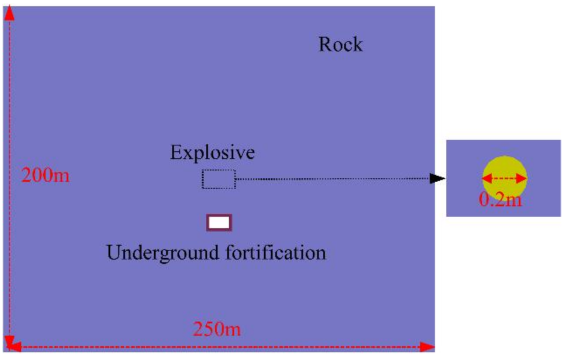


Figure 1. Numerical model of underground fortification and rock mass.

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 and concrete.

Material	Density (kg/m^3)	Elastic modulus (GPa)	Cohesive strength (MPa)	Tensile strength (MPa)	Friction angle (°)
Rock	2300	10	8	4	40
Concrete	2500	35	25	12	62.5

2.2. Numerical results

To study the influence of explosion distance on the damage degree of underground fortification, the distance d between the explosive and underground fortification is set to four values, d = 5 m in case A, d = 10 m in case B, d = 15 m in case C and d = 20 m in case D. Based on the CDEM numerical method, the dynamic mechanical response of underground fortification under blast load is simulated, and the displacement and fracture characteristics in four cases are investigated.

2.2.1. *Displacement characteristic.* The resultant displacement nephograms at t = 1.00 s in four cases are plotted in figure 2, and only the underground fortification and rock mass near the underground fortification are plotted.

It is observed that there are obvious differences in the displacement characteristic of underground fortification and rock mass in four cases. As the explosion distance increases, the damage degree of underground fortification and rock mass weakens, and the volume of rock mass entering the underground fortification decreases. When the explosion distance d = 5 m and 10 m (figure 2(a), figure 2(b)), the top concrete wall of underground fortification and the rock above crack and collapse, and the height of collapsed rock are basically the same. The left and right concrete walls of underground fortification also crack and slip, while the displacement value is small. When the explosion distance d = 15 m (figure 2(c)), the top concrete wall of underground fortification and the rock above crack and collapse, and the area of collapsed rock decreases. In addition, the displacement of the left and right concrete walls decreases. When the explosion distance d = 20 m (figure 2(d)), the top concrete wall of underground fortification is not completely destroyed, and only part of the concrete cracks and collapses. Due to the support of concrete walls, the rock above does not collapse.

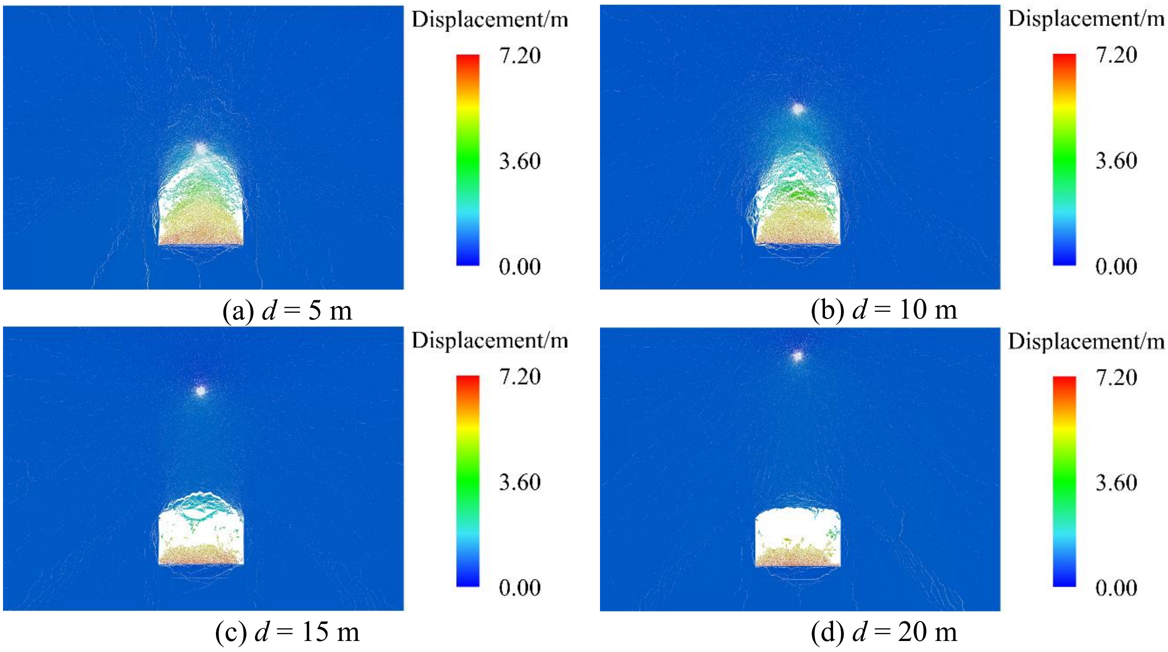


Figure 2. Resultant displacement nephograms near the underground fortification.

With the increase of explosion distance d, the volume V_r of rock mass entering the underground fortification is plotted in figure 3. It is observed that as the distance increases, the volume V_r gradually decreases, but the decrease rate of V_r does not maintain a constant value. When the distance d increases from 5 m to 10 m, the volume V_r decreases slightly, and the value is 2.00%. When the distance d increases from 10 m to 20 m, the volume V_r decreases rapidly. When the distance d = 20 m, the top concrete wall of underground fortification still has bearing capacity, and no rock enters the underground fortification. Therefore, it is concluded that in the different distance ranges, the increase of explosion distance d has different influences on the damage degree of underground fortification and rock mass.

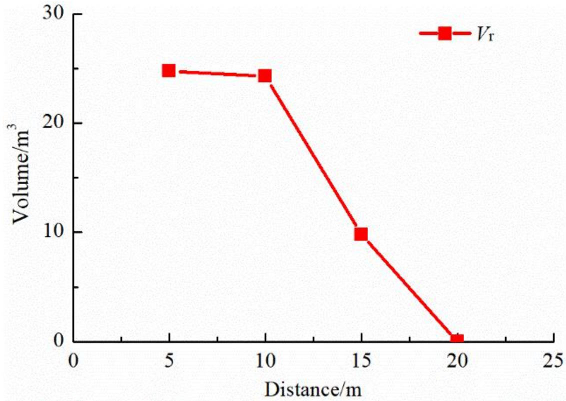


Figure 3. Change curve of rock volume V_r.

2.2.2. *Fracture characteristic.* To quantitatively investigate the fracture evolution characteristic of underground fortification under blast load, a dimensionless index, crack ratio α, is introduced, and it is written as

$$\alpha = \frac{S_c}{S_a} \tag{1}$$

where S_c is the area of cracked interface between concrete elements, S_a is the area of all interface between concrete elements.

The time-history curve of crack ratio α is plotted in figure 4. It is observed that the value of crack ratio α gradually decreases with the increase of distance, while the change trend is similar, which has the four-stage characteristic. In the case of d = 20 m, three inflection points (point A, point B, point C) are drawn on the curve.

In the OA range, due to the strong impact of explosion shock wave, the concrete walls of underground fortification crack, resulting in a sharp increase in the crack ratio α. In the AB range, the explosion gas disappears and the explosion shock wave decays. Due to the interaction between the rock mass and the concrete wall, crack ratio α gradually increases, and the increase trend of α in four cases is different. With the increase of distance d, the damage degree of the top concrete wall and the rock above weakens, and the increase amount of crack ratio α gradually decreases. In the BC range, the collapsed concrete reaches the bottom concrete wall, where the concrete cracks during the interaction process, resulting in the crack ratio α increasing again. In the CD range, due to the interaction between the rock mass and the concrete wall, a small amount of interface cracks, resulting in a slight increase in the crack ratio α.

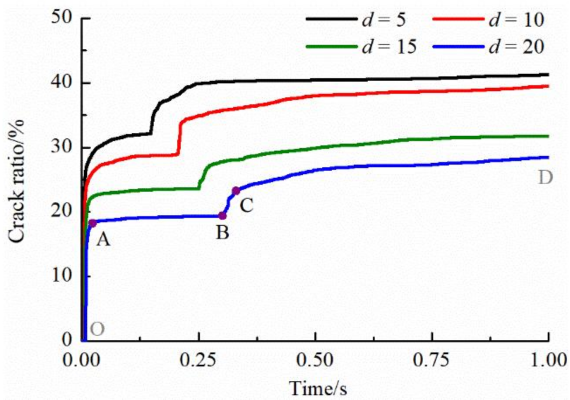
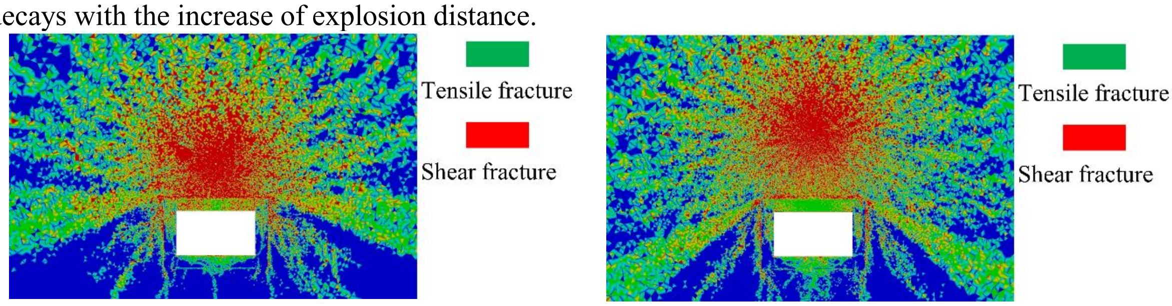


Figure 4. Time-history curve of crack ratio α.

To investigate the spatial distribution and fracture type of cracked interface, the fracture nephograms at t = 1.00 s in four cases are plotted in figure 5.The displacement value is set to zero to facilitate the observation of spatial position of cracked interface.

It is observed that the rock near the explosive mainly undergoes shear fracture, and with the increase of distance from the explosive, the proportion of rock undergoing tensile fracture gradually increases. The fracture characteristic of underground fortification is basically the same in four cases, and the fracture type includes tensile fracture and shear fracture. The damage degree of top concrete wall is the most severe. For the left and right concrete walls, the damage degree of the upper part is severe, and the damage degree of the lower part is weak. For the bottom concrete wall, the cracked interface is concentrated in the middle part, and the damage degree of the left and right parts is weak. In addition, some change in the fracture characteristic occurs with the increase of explosion distance. When the explosion distance d = 5 m (figure 5(a)), the top concrete wall undergoes tensile fracture and shear fracture. As the distance increases, the proportion of interface undergoing tensile fracture gradually increases. When the explosion distance d = 20 m (figure 5(d)), the top concrete wall mainly undergoes tensile fracture. For the left, right and bottom concrete walls, the damage degree gradually decays with the increase of explosion distance.



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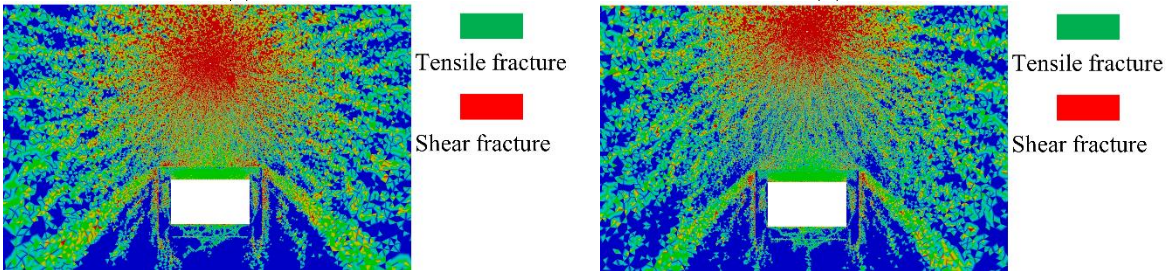
(a) d = 5 m (b) d = 10 m



(c) d = 15 m (d) d = 20 m

Figure 5. Fracture nephograms near the underground fortification.

3. Conclusions

To study the influence of explosion distance on the damage characteristic of underground fortification, the full-time numerical simulation of dynamic mechanical response of underground fortification under blast load is conducted, and the displacement and fracture characteristics are quantitatively analyzed. The following conclusions can be drawn:

(1) As the explosion distance increases, the damage degree of underground fortification and rock mass weakens. When the distance increases from 5 m to 20 m, the volume V_r of rock entering the underground fortification decreases from 24.78 m^3 to 0 m^3, and the decrease rate of V_r does not maintain a constant value.

(2) The change trend of crack ratio α has the four-stage characteristic, and α increases rapidly during the explosion initiation process. The fracture characteristic of underground fortification is basically the same in four cases, and the damage degree of top concrete wall is the most severe. As the distance increases, the proportion of interface undergoing tensile fracture at the top concrete wall gradually increases.

Acknowledgements

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