



Prediction Model of Rock Displacement and Porosity in Deep Hole Blasting

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Abstract. In mine production, the prevention and control of toxic and harmful gases after blasting is very important. Extraction is an effective method to reduce toxic and harmful gases. Efficient extraction depends on the accurate grasp of the gas distribution position. In order to grasp the distribution law of rock cracks after blasting and optimize the extraction scheme, this paper constructs a new mathematical model to calculate the change of displacement and porosity after blasting based on quasi-static and dynamic theory, and takes the blasting of Kuangou Coal Mine as an example. The results show that the ratio of the total displacement under the action of blasting shock wave to the total displacement under the action of blasting gas is 1 : 2.537. The ratio of the total displacement under the action of blasting shock wave to the radius of the crushing zone under the action of blasting gas is 1 : 1.33, and the ratio of the radius of the fracture zone is 1 : 1.14. From the relationship of radius ratio, it can be seen that the blasting shock wave mainly leads to the generation of rock cracks, and the action of blasting gas mainly leads to the expansion of cracks. The toxic and harmful gases after blasting are mainly concentrated in the blasting cavity and the fracture space in the crushing area. When optimizing the blasting scheme, the main direction should be to increase the range of fracture zone and reduce the range of crushing zone. By optimizing the blasting parameters such as hole diameter, the extraction effect of toxic and harmful gases after blasting can be effectively improved, which provides theoretical basis and practical guidance for gas control in engineering blasting.

Keywords: deep hole blasting; porosity; displacement patterns; explosion mechanics; computational model

1 Introduction

In China's coal production process, coal seam extraction often faces the threat of rock-burst disasters, posing significant risks to mine safety. To effectively mitigate rock-bursts, mines commonly employ advanced deep-hole pre-split blasting technology^[1]. However, the blasting process generates a large amount of toxic and hazardous gases, which not only threaten the health of underground workers but also pose potential safety hazards. Therefore, controlling the release and dispersion of these gases during blasting is crucial. Among the existing mitigation measures, gas extraction technology is one of the most effective methods for reducing harmful gas concentrations in underground mines^[2]. The design of an efficient extraction system must be based on the migration patterns of post-blasting toxic gases, which primarily accumulate in the fractured rock space. The changes in this fractured space can be characterized by porosity. Therefore, studying the variation of rock porosity after blasting is essential for understanding the distribution of toxic gases and optimizing gas extraction strategies. The theory of rock blasting^[3] primarily involves two key mechanisms: (1) the dynamic effects of explosion-induced stress waves and (2) the quasi-static effects of detonation gases. Current research generally agrees that rock fragmentation results from the combined action of these two mechanisms, though their relative contributions vary depending on blasting parameters and charge conditions. As early as 1971, Kutter et al.^[4] proposed that, beyond the instantaneous destruction caused by stress waves, detonation gases form a quasi-static pressure field inside the rock, exerting prolonged influence at relatively low pressures and promoting further crack propagation. Hagan^[5] supported this perspective and explicitly referred to this phenomenon as the "gas wedge effect." Daehnke^[6] conducted experimental studies showing that only 8% of crack propagation is driven by stress waves, whereas 92% is caused by the pressure of detonation gases. Huilin Liu et al.^[7] investigated the dynamic response of hard rock blasting under geostress conditions, while TLi T et al.^[8] analyzed the influence of different coupling media on rock fragmentation in bench blasting. Lak M et al.^[9] utilized a two-dimensional elastodynamic Green's function for numerical modeling of rock blasting. Yuchenglong et al.^[10] derived a quasi-static computational formula for the damage zone of spherical charge blasting based on the elastic-fracture-crushing response model and the Mohr-Coulomb criterion. Despite extensive theoretical and experimental research on rock blasting, most studies have focused on optimizing blasting performance, such as analyzing stress wave propagation and damage zone distribution. However, there has been relatively little investigation into the evolution mechanisms of rock displacement and porosity across the two distinct blasting phases: the stress wave action phase and the detonation gas action phase. To address this issue, this study develops a mathematical model based on quasi-static and dynamic theories to calculate rock displacement and porosity variations after blasting. A systematic analysis of the evolution of displacement and porosity during the blasting process is conducted, and the porosity variation patterns are revealed based on their interrelationship. The findings provide theoretical insights into the storage and migration mechanisms of toxic gases, offering valuable guidance for optimizing blasting parameters and designing efficient gas extraction systems.

2 Model Establishment

2.1 Blasting Zoning and Calculation Conditions

The response of rock under explosive loading can be divided into two sequential stages:

- (1) the initial rock failure and crack formation induced by the explosion shock;
- (2) the subsequent crack propagation driven by the quasi-static effect of detonation gases.

Under the combined effects of shock waves and stress waves, the rock medium exhibits either a fragmented state or a damaged state. Based on the degree of rock damage, the blasting-affected zone can be classified into three regions: the crushing zone, the fracture zone, and the elastic deformation zone^[11], as shown in Figure 1.

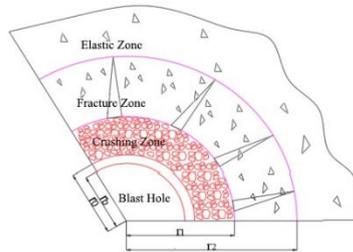


Fig. 1. Rock blasting failure zoning diagram

To calculate the displacement and porosity of rock in deep-hole blasting, the blast hole is considered as an infinitely long cylindrical cavity within a homogeneous rock mass, subjected to a radially uniform internal blasting load, with the following assumptions:

- (1) The cylindrical cavity extends infinitely along the axial direction, allowing the problem to be treated as an axisymmetric plane strain problem.
- (2) During the explosive shock wave phase, the rebound effect is neglected due to the extremely short duration.
- (3) During the detonation gas phase, the rock in the crushing zone is assumed to be isotropic and incompressible.
- (4) The expansion of detonation gases is considered adiabatic, and the volume of gas entering rock fractures is neglected.

2.2 Derivation of the Displacement Distribution Law Under the Action of Blasting Shock Waves

2.2.1 Calculation of Blasting Shock Load and Attenuation Law of Shock Waves.

The attenuation of the blasting shock wave load is influenced by both time and the distance from the blasting center. The effect of the distance r from the blasting center on shock wave load attenuation is typically analyzed in three distinct zones: the crushing zone, the fracture zone, and the elastic deformation zone. In the crushing zone, the

shock wave propagates through the rock, which can be approximated as a fluid. The attenuation law of the shock wave pressure p with distance r from the blasting center is given by^[11].

$$p = p_b \tilde{r}^{-\alpha_0} \tag{1}$$

In $\tilde{r} = r/r_b$; r is the distance from the blasting center ; r_b is the radius of the hole ; α_0 is the pressure attenuation index, for the shock wave, take $\alpha_0 = 2 + \frac{\mu}{1-\mu}$.

In the fracture zone, the blasting shock wave propagates in the form of stress waves. The attenuation law is similar to that of the shock wave, but the attenuation coefficient is smaller than that of the shock wave. The attenuation law of the stress wave is given by

$$P = p_b \left(\frac{r_b}{r_1} \right)^{\alpha_0} \left(\frac{r_1}{r} \right)^\alpha \tag{2}$$

In the formula : the stress wave attenuation index $\alpha = 2 - \mu / (1 - \mu)$, μ is the dynamic poisson 's ratio, take 0.8 times of the static poisson 's ratio.

In the elastic deformation zone, the stress wave further attenuates into seismic waves. The attenuation law is given by

$$P = p_b \left(\frac{r_b}{r_1} \right)^{\alpha_0} \left(\frac{r_1}{r_2} \right)^\alpha \left(\frac{r_2}{r} \right)^{\alpha_1} \tag{3}$$

In the formula, the attenuation index $\alpha_1 = 1 \sim 2$;

2.2.2 Study on the Distribution Law of Rock Strain Rate in Different Blasting Zones.

Under the action of the blasting shock wave, the rock mass experiences intense dynamic responses. Since the strain rate of the rock near the borehole is difficult to measure, the relationship between radial strain rate and vibration velocity is introduced based on the displacement compatibility equation for cylindrical waves^[12].

$$\varepsilon = \frac{\partial \mu}{\partial r} \rightarrow \dot{\varepsilon} = \frac{\partial \mu}{\partial r \partial t} = \frac{\partial v}{\partial r} \tag{4}$$

In the formula : ε is the radial strain, μ is the displacement at radius r ; r is the distance from the center of the borehole ; $\dot{\varepsilon}$ is the radial strain rate ; v is the velocity at radius r .

By combining the relationship between the blasting load and time, the relationship between particle vibration velocity and time is derived as

$$f(t) = v_{v_0}(t) = \frac{-a\rho_0 + \sqrt{(a\rho_0)^2 + 4b\rho_0 P(t)}}{2b\rho_0} \tag{5}$$

Because blasting shock wave leads to rock blasting vibration, the attenuation law of blasting shock wave and particle vibration velocity is the same. Combined with the attenuation law of blasting shock wave, the vibration attenuation law of blasting rock particle can be obtained. The strain rate can be obtained by partial derivative of particle vibration velocity to blasting r [13].

The attenuation laws of particle vibration velocity and strain rate with the distance r from the center of the blast hole in the semi-crushing zone, the fracture zone and the elastic deformation zone of the fracture zone are as follows :

$$\left\{ \begin{array}{l} \text{crushing zone} \\ \text{fracture zone} \\ \text{elastic zone} \end{array} \right\} \left\{ \begin{array}{l} \text{velocity of vibration : } v_r(t) = v_{r0}(t) \left(\frac{r}{r_b}\right)^{-\alpha_0} \\ \text{strain rate : } \varepsilon_r(t) = \alpha_0 \frac{f(t)}{r_b} \left(\frac{r}{r_b}\right)^{-(\alpha_0+1)} \\ \text{velocity of vibration : } v_r(t) = v_{r0}(t) \left(\frac{r_1}{r_b}\right)^{-\alpha_0} \left(\frac{r}{r_1}\right)^{-\alpha} \\ \text{strain rate : } \varepsilon_r(t) = v_{r0} \left(\frac{r_1}{r_b}\right)^{-\alpha_0} \left(\frac{r}{r_1}\right)^{-(\alpha+1)} \frac{\alpha}{r_1} \\ \text{velocity of vibration : } v_r(t) = v_{r0}(t) \left(\frac{r_1}{r_b}\right)^{-\alpha_0} \left(\frac{r_2}{r_1}\right)^{-\alpha} \left(\frac{r}{r_2}\right)^{-\alpha_1} \\ \text{strain rate : } \varepsilon_r(t) = v_{r0}(t) \left(\frac{r_1}{r_b}\right)^{-\alpha_0} \left(\frac{r_2}{r_1}\right)^{-\alpha} \left(\frac{r}{r_2}\right)^{-(\alpha_1+1)} \frac{\alpha_1}{r_2} \end{array} \right. \quad (6)$$

The completion time t of blasting shock wave expansion is selected. At this time, the ultimate strain for rock failure at the boundary between the fracture zone and the crushing zone is given by $\varepsilon_{\text{limit}} = \frac{[\sigma_s](1+\nu)}{E}$, At this point, the crushing zone is considered as incompressible fragments with strain equal to the rock’s ultimate strain. The strain in the fracture zone and elastic zone follows the elastic principle under the blasting shock wave [14]. By combining the attenuation law, the strain of the rock element in the fracture zone at the time when the blasting shock wave completes cavity expansion with respect to the distance r from the blasting center is given by

$$\varepsilon_{\text{rima}} = \varepsilon_{\text{limit}} \left(\frac{r_1}{r}\right)^{a+1} \quad (7)$$

The strain of the rock element in the elastic zone at the time with respect to the distance r from the blasting center is given by

$$\varepsilon_{\text{elasticity}} = \varepsilon_{\text{limit}} \left(\frac{r_1}{r_2}\right)^{a+1} \left(\frac{r_2}{r}\right)^{a_1+1} \quad (8)$$

2.2.3 Displacement Law in Different Blasting Zones.

Study on the Displacement Law in the Elastic Zone

At the time t , the displacement in the elastic deformation zone as a function of the distance r from the blasting center is given by

$$u = \frac{(1+\nu)[\sigma_s]}{Ea_1} \left(\frac{r_1}{r_2}\right)^{a+1} \left(\frac{r_2^{a_1+1}}{r^{a_1}}\right) \tag{9}$$

When the distance from the blasting center is the radius r_2 of the fracture zone, the displacement at the outer boundary of the fracture zone can be derived from equation (26) as

$$u_{r_2} = \frac{(1+\nu)[\sigma_s]}{Ea_1} \left(\frac{r_1}{r_2}\right)^{a+1} r_2 \tag{10}$$

Study on the Displacement Law in the Fracture Zone

Within the fracture zone, the blasting shock wave propagates in the form of stress waves, doing work and causing displacement. At the time t , the displacement in the fracture zone as a function of the distance r from the blasting center is given by

$$u_r = \frac{(1+\nu)[\sigma_s]}{E} \left[\frac{r_1}{a} \left(\frac{r_1}{r}\right)^a + \left(\frac{1}{a_1} - \frac{1}{a}\right) \left(\frac{r_1}{r_2}\right)^{a+1} r_2 \right] \tag{11}$$

When the distance from the blasting center is the radius r_1 of the crushing zone, the displacement at the outer boundary of the fracture zone can be derived from equation (29) as

$$u_{r_1} = \frac{(1+\nu)[\sigma_s]}{E} \left[\frac{r_1}{a} + \left(\frac{1}{a_1} - \frac{1}{a}\right) \left(\frac{r_1}{r_2}\right)^{a+1} r_2 \right] \tag{12}$$

Study on the Displacement Law in the Crushing Zone

Within the crushing zone, the blasting shock wave propagates in the form of a shock wave, doing work and causing displacement. At the time t , the displacement in the crushing zone as a function of the radius r is given by

$$u_r = (r_1 - r) \frac{(1+\nu)[\sigma_s]}{E} + \frac{(1+\nu)[\sigma_s]}{E} \left[\frac{r_1}{a} + \left(\frac{1}{a_1} - \frac{1}{a}\right) \left(\frac{r_1}{r_2}\right)^{a+1} r_2 \right] \tag{13}$$

When the distance from the blasting center is the borehole radius, the displacement at this point is the maximum displacement caused by the blasting shock wave expansion. From this, the expansion radius of the blasting shock wave can be derived as

$$r_0 = (r_1 - r_b) \frac{(1+\nu)[\sigma_s]}{E} + \frac{(1+\nu)[\sigma_s]}{E} \left(\frac{r_1}{a} + \left(\frac{1}{a_1} - \frac{1}{a} \right) \left(\frac{r_1}{r_2} \right)^{a+1} \right) + r_b \tag{14}$$

According to reference [15], the relationship between the blasting shock wave expansion radius and the crushing zone radius is given by:

$$r_0 = \left[r_1^2 - (r_1^2 - r_b^2) \frac{a + (b-1) v_0}{a + b v_0} \right]^{\frac{1}{2}} \tag{15}$$

By combining equations (14) and (15), the relationship between the crushing zone radius, borehole radius, rock properties, and detonation pressure can be derived as:

$$\left[r_1^2 - (r_1^2 - r_b^2) \frac{a + (b-1) v_0}{a + b v_0} \right]^{\frac{1}{2}} = (r_1 - r_b) \frac{(1+\nu)[\sigma_s]}{E} + \frac{(1+\nu)[\sigma_s]}{E} \left(\frac{r_1}{a} + \left(\frac{1}{a_1} - \frac{1}{a} \right) \left(\frac{r_1}{r_2} \right)^{a+1} \right) + r_b \tag{16}$$

The relationship between the crushing zone radius r_1 and the fracture zone radius r_2 is given by:

$$r_2 = \left[\frac{\lambda [\sigma_s]}{\sigma_{td} + \sigma_{\theta_{ground}}} \right]^{\frac{1}{\alpha}} r_1 \tag{17}$$

2.3 Study on the Distribution Law of Blasting Displacement Due to Work Done by Blast-Generated Gases

2.3.1 Mechanical Analysis under the Quasi-Static Stress Field Condition after Blasting.

Since the length of the blasting borehole is much greater than the expansion radius after blasting, and there are no other external forces at both ends of the borehole, the rock stress state near the blasting cavity can be treated as a plane strain problem. which can be analyzed using the stress state of a thick-walled cylinder problem. As shown in Figure 2.

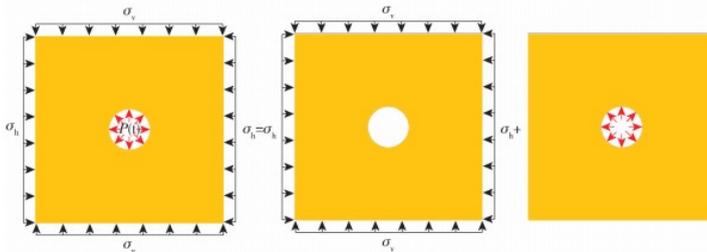


Fig. 2. Distribution of ground stress

Under the action of in-situ stress, the static stress distribution around the borehole can be solved using the following formula ^[16]:

$$\begin{cases} \sigma_r = -\sigma_0 \left(1 - \frac{r_b^2}{r^2} \right) - \frac{r_0^2}{r^2} p_0 \\ \sigma_\theta = -\sigma_0 \left(1 + \frac{r_b^2}{r^2} \right) + \frac{r_0^2}{r^2} p_0 \lambda \end{cases} \quad (18)$$

2.3.2 Calculation of Blast Cavity Radius and Blasting Damage Zone.

After the shock wave expansion process ends, the blast-generated gas rapidly fills the cavity and continues to act on the cavity wall in the form of quasi-static forces, causing the cavity wall rock to continue radial movement and the cavity to continue expanding.

Ignoring gas leakage through the borehole and fractures, for adiabatic expansion, the final radius of the blasting cavity is:

$$r_0 = \begin{cases} r_b (P_b / P_s)^{1/6} & \text{-----} (P_s > P_k) \\ r_b (P_b / P_k)^{1/6} (P_k / P_s)^{3/8} & \text{-----} (P_s < P_k) \end{cases} \quad (19)$$

The corresponding blasting gas pressure at this point is

$$p_0 = p_b \left(\frac{r_b}{r_0} \right)^{2\gamma} \quad (20)$$

As the blast-generated gas continues to do work, the distribution of the rock damage zone changes. When the radial pressure equals the compressive strength of the rock, the crushing zone radius r_1 can be determined as:

$$r_1 = \sqrt{\frac{P_0}{[\sigma_s]}} r_0 \quad (21)$$

When the tangential stress in the rock equals the tensile strength, $\sigma_\theta = \sigma_t$, The radius of the fracture zone r_2 can be determined, $\sigma_r = \sigma_0 (1 - r_b^2/r^2)$, $r_b^2/r^2 \ll 1$, $\sigma_r = \sigma_0$, The corresponding radius of the fracture zone r_2 is

$$r_2 = \sqrt{\frac{\lambda p_0 r_0^2}{\sigma_t + \sigma_0}} \quad (22)$$

2.3.3 Study on the Displacement Patterns in Different Blasting Regions.

As the blast-generated gas continues to do work after the shock wave ends, the rock suffers further damage, and the displacement increases. Under the combined effect of the blast-generated gas and in-situ stress, the displacement formula for the elastic zone is given by^[11].

$$u_r = \frac{(1+\nu)r_2^2}{Er} \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \quad (23)$$

When the distance from the blasting center, r , equals r_2 , the displacement at the boundary of the fracture zone can be determined as:

$$u_{r_2} = \frac{1+\nu}{E} r_2 \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \quad (24)$$

In the formula, ν is the Poisson's ratio, E is the elastic modulus, r_2 is the radius of the fracture zone, r is the distance from the center of the blast hole, $[\sigma_t]$ is the tensile strength, and σ_0 is the original ground stress.

In the fracture zone, based on the relationship between rock stress and displacement changes $\sigma_r = \frac{E}{(1+\nu)} \varepsilon_r$. The strain at a distance r from the blasting center is derived as

$$\varepsilon_r = \frac{(1+\nu) \left(\frac{r_0^2}{r^2} p_0 \right)}{E} \quad (25)$$

The displacement formula for the fracture zone is

$$u_r = \frac{(1+\nu)}{E} r_0^2 p_0 \left(\frac{1}{r} - \frac{1}{r_2} \right) + \frac{1+\nu}{E} r_2 \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \quad (26)$$

When the distance from the blasting center is the radius r_1 of the crushing zone, the displacement at the outer boundary of the crushing zone can be determined from formula (41) as

$$u_{r_1} = \frac{(1+\nu)}{E} r_0^2 p_0 \left(\frac{1}{r_1} - \frac{1}{r_2} \right) + \frac{1+\nu}{E} r_2 \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \quad (27)$$

The rock surrounding the explosive undergoes strong compression and shear under the action of the blast-generated gas, leading to the structural failure of the entire rock mass. The rock in this region can be considered isotropic and incompressible, and its strain can be treated as average. Displacement at the inner boundary of the crushing

zone $u_{r=r_b} = r_0 - r_b$, The displacement at the outer boundary of the crushing zone is, from which the strain can be determined as

$$\varepsilon = \frac{r_0 - r_b - u_{r_1}}{r_1 - r_b} \tag{28}$$

The displacement formula for the crushing zone is

$$u = \frac{r_0 - r_b - u_{r_1}}{r_1 - r_b} (r_1 - r) + u_{r_1} \tag{29}$$

2.4 Study on the Distribution Law of Porosity in Blasted Rock

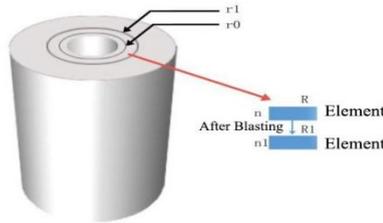


Fig. 3. Relationship between blasting porosity and displacement

The variation law of porosity after blasting needs to be indirectly determined through displacement laws. For cylindrical charge advanced blasting, the influence of the ends is ignored, and only the porosity change in the middle is considered. The displacement of the rock after blasting is shown in Figure 3. It is assumed that the rock after blasting is isotropic. Before blasting, the distance from the rock to the borehole center is r , the radial length of the rock element is n , and the circumferential length of the rock is R . After blasting, the distance of the rock element from the blasting center is $r+u$, the radial length of the rock element is n_1 , and the circumferential length is R_1 . Based on the definition of porosity and considering the displacement of the rock element, the relationship between displacement and porosity is derived as

$$k = \frac{\Delta_{\text{void}}}{\Delta_{\text{total}}} = \frac{n_1 \cdot R_1 - n \cdot R(1 - k_0)}{n_1 R_1} = 1 - \frac{1}{1 - \varepsilon_{\text{radial direction}}} \cdot \frac{r(1 - k_0)}{(r + u)} \tag{30}$$

In the formula : ε_{per} is the radial strain, where the tensile strain is positive, the compressive strain is negative, k_0 is the initial porosity, u is the radial displacement of the blasting rock at r .

According to equation (30), the porosity of the rock after blasting is not only related to the initial porosity but also to the distance r from the blasting center, its displacement, and the strain caused by the pressure exerted on it.

Based on the displacement formula for the elastic zone caused by the blast shock wave at time t derived earlier, and combining the stress-strain relationship, the following is obtained.

$$k_{\text{elastic zone}}^{\text{Blasting shock wave stage}} = 1 - \frac{1}{1 - \frac{[\sigma_s]}{E} \left(\frac{r_1}{r_2} \right)^{a+1} \left(\frac{r_2}{r} \right)^{a_1+1}} \cdot \frac{r(1-k_0)}{\left(r + \frac{[\sigma_s]}{E a_1} \left(\frac{r_1}{r_2} \right)^{a+1} \left(\frac{r_2}{r^{a_1}} \right) \right)} \quad (31)$$

Similarly, the formula for the change in porosity of the fracture zone with respect to the distance r from the center of the borehole is obtained as follows.

$$k_{\text{fracture zone}}^{\text{Blasting shock wave stage}} = 1 - \frac{1}{1 - \frac{[\sigma_s]}{E} \left(\frac{r_1}{r} \right)^{a+1}} \cdot \frac{r(1-k_0)}{\left(r + \frac{[\sigma_s]}{E} \left(\frac{r_1}{a} \left(\frac{r_1}{r} \right)^a + \left(\frac{1}{a_1} - \frac{1}{a} \right) \left(\frac{r_1}{r_2} \right)^{a+1} r_2 \right) \right)} \quad (32)$$

The formula for the change in porosity of the crushing zone with respect to the distance r from the center of the borehole is as follows.

$$k_{\text{crushing zone}}^{\text{Blasting shock wave stage}} = 1 - \frac{1}{1 - \frac{[\sigma_s]}{E}} \cdot \frac{r(1-k_0)}{\left(r + (r_1 - r) \frac{[\sigma_s]}{E} + \frac{[\sigma_s]}{E} \left(\frac{r_1}{a} + \left(\frac{1}{a_1} - \frac{1}{a} \right) \left(\frac{r_1}{r_2} \right)^{a+1} r_2 \right) \right)} \quad (33)$$

Based on the displacement formula for the elastic zone induced by the work done by the explosive gases, and combining the displacement with the strain generated by the explosive gases, the formula for the change in porosity of the elastic zone during the explosive gas phase with respect to the distance r from the center of the borehole is as follows.

$$k_{\text{elastic zone}}^{\text{Explosive gas phase}} = 1 - \frac{1}{(1+\nu) \left(\frac{r_2^2}{r^2} \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \right)} \cdot \frac{r(1-k_0)}{\left(r + \frac{(1+\nu)r_2^2}{E r^2} \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \right)} \quad (34)$$

Based on the displacement formula for the fracture zone induced by the work done by the explosive gases, and combining the displacement with the strain generated by the explosive gases, the formula for the change in porosity of the fracture zone during the explosive gas phase with respect to the distance r from the center of the borehole is as follows.

$$k_{\text{fracture zone}}^{\text{Explosive gas phase}} = 1 - \frac{1}{(1+\nu) \left(\frac{r_0^2}{r^2} p_0 \right)} \cdot \frac{r(1-k_0)}{\left(r + \frac{(1+\nu)}{E} r_0^2 p_0 \left(\frac{1}{r} - \frac{1}{r_2} \right) + \frac{1+\nu}{E} r_2 \left(\frac{[\sigma_t] + \sigma_0}{\lambda} \right) \right)} \quad (35)$$

Based on the displacement formula for the crushing zone induced by the work done by the explosive gases, and combining the displacement with the strain generated by the explosive gases, the formula for the change in porosity of the crushing zone during

the explosive gas phase with respect to the distance r from the center of the borehole is as follows.

$$k_{\text{crushing zone}}^{\text{Explosive gas phase}} = 1 - \frac{1}{1 - \frac{r_0 - r_b - u_{r_1}}{r_1 - r_b}} \cdot \frac{r(1 - k_0)}{r + \frac{r_0 - r_b - u_{r_1}}{r_1 - r_b}(r_1 - r) + u_{r_1}} \tag{36}$$

3 Comparative Study of Displacement and Porosity Distribution Laws in Different Blasting Phases

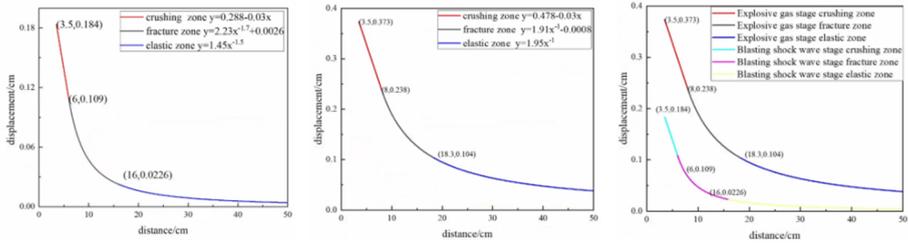
The project is based on the advanced deep hole roof blasting at the I010203 working face of the Kuangou coal mine, with the blasting parameters shown in Table 1. By substituting the parameters into the above formulas, the specific displacement variation law is obtained as shown in Figure 4. The range of each blasting damage zone and the specific displacement variation under the action of the blasting shock wave are shown in Figure 5(a), and under the action of the blasting gas, the range of each blasting damage zone and the specific displacement variation are shown in Figure 5(b).

Table 1. Rock and explosives parameters

rock parameter		explosive parameters	
density(kg/m ³)	2600	density(kg/m ³)	1200
bulk modulus(GPa)	30	detonation velocity(m/s)	4100
poisson ratio	0.2	Coupling coefficient of radial charge	0.7
tensile strength(MPa)	3.6	Coupling coefficient of axial charge	1
compressive strength(MPa)	120	γ	3
ground stress(MPa)	10		

According to Fig.4 (a), the total displacement of the expansion cavity under the action of blasting shock wave is 0.147 cm, the radius of the expansion cavity is 3.647 cm, the ratio of the radius of the expansion cavity to the radius of the blast hole is 1.042, the radius of the crushing zone is 6cm, the strain generated in the crushing zone is 0.06cm, accounting for 40.09 % of the total displacement, the radius of the fracture zone is 16cm, the strain generated in the fracture zone is 0.0687cm, accounting for 46.7 % of the total displacement, and the strain generated in the elastic zone is 0.0181cm, accounting for 12.3 % of the total strain.

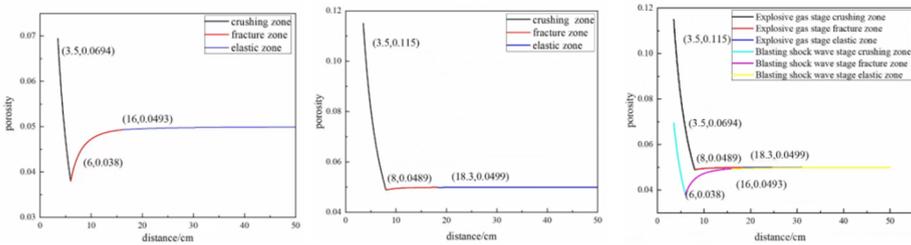
According to Fig.4 (b), the total displacement of the expansion cavity under the action of detonation gas is 0.373 cm, the radius of the expansion cavity is 3.873 cm, the ratio of the radius of the expansion cavity to the radius of the blast hole is 1.107, the radius of the crushing zone is 8cm, the strain generated in the crushing zone is 0.135 cm, accounting for 36.2 % of the total displacement, the radius of the fracture zone is 18.3 cm, the strain generated in the fracture zone is 0.134 cm, accounting for 35.9 % of the total displacement, and the strain generated in the elastic zone is 0.104 cm, accounting for 27.9 % of the total strain.



(a) Shock wave displacement (b) Explosive gas displacement (c) Comparison of the two phases

Fig. 4. Distribution of displacement variation

According to Fig.4 (c), the ratio of the total displacement under the action of blasting shock wave to the total displacement under the action of blasting gas is 1 : 2.537. The ratio of the total displacement under the action of the blasting shock wave to the radius of the crushing zone under the action of the blasting gas is 1 : 1.33, and the ratio of the radius of the fracture zone is 1 : 1.14. The blasting shock wave mainly leads to the generation of rock cracks, and the action of the blasting gas mainly leads to the expansion of cracks.



(a) Shock wave porosity (b) Explosive gas porosity (c) Comparison of the two phases

Fig. 5. Variation of rock porosity

According to Fig.5 (a) and (b), the porosity of rock under blasting shock wave decreases first and then increases with the increase of distance from blasting center. The change trend of porosity is related to blasting zone. The porosity of crushing zone decreases linearly with the increase of distance from blasting center. The maximum value of rock porosity is 0.0694 at the radius of blasthole cavity, and the minimum value of porosity is 0.038 at the radius of crushing zone, which is lower than the initial porosity. The porosity of fracture zone and elastic zone increases with the increase of distance, showing an exponential function. It changes rapidly at the beginning and then tends to be stable. However, the overall porosity is lower than the initial porosity. The porosity of the rock crushing zone under the action of detonation gas decreases with the increase of distance, showing a linear decrease. The maximum porosity of the rock is 0.0115 at the radius of the blasthole cavity, and the minimum porosity is 0.0489 at the

radius of the crushing zone. The porosity of the fracture zone and the elastic zone is slightly lower than the initial porosity, and the change is not obvious.

As shown in Figure 5(c), at the same distance from the blasting center, the porosity under the action of explosive gases is greater than that under the action of blast shock waves. In the fracture and elastic zones, the blast shock wave causes a reduction in rock porosity, and the primary changes in porosity occur during the explosive gas phase.

4 Engineering Application

In blasting engineering, the analysis of porosity distribution characteristics indicates that the toxic and harmful gases generated after blasting are primarily concentrated in the blast cavity and the fracture space of the crushed zone, whereas the fissure zone contains relatively fewer fractures. Therefore, to enhance the efficient accumulation and extraction of toxic gases post-blasting, it is essential to minimize the radius of the crushed zone as much as possible. In deep-hole presplitting blasting, as there is no need for muck pile recovery, the primary focus should be on optimizing blasting parameters to reduce the extent of the crushed zone. Typically, this optimization involves adjusting blasting parameters, selecting appropriate explosives, and improving charging methods. To verify the impact of reducing the crushed zone radius on extraction efficiency, this study conducted blasting experiments using boreholes with smaller diameters while ensuring effective blasting performance.

Considering the field conditions and equipment configuration at Kuangou Coal Mine, the deep-hole blasting experiment in the I010206 working face involved two different borehole diameters: $\Phi 94$ mm and $\Phi 75$ mm. In Scheme 1, boreholes with a diameter of 94 mm were used, with a charge linear density of 4.2 kg/m, and the blast holes were grouped at 7.5 m intervals, with each group containing six boreholes. In Scheme 2, boreholes with a diameter of 75 mm were employed, with a charge linear density of 2.8 kg/m, and the blast holes were grouped at 5 m intervals, also with six boreholes per group. The specific borehole layout and charge structure are shown in Figure 6.

During the blasting process, a gas drainage steel pipe was installed at the lower part of the blast hole opening and secured to the tunnel roof using two anchor bolts. One end of the drainage pipe covered the charged blast hole, while the other end was connected to the main gas drainage pipeline via a flexible hose to maximize the collection and extraction of toxic and harmful gases generated after blasting. A schematic diagram of the gas extraction at the pre-split hole mouth is shown in Figure 7.

To evaluate the impact of different borehole diameters on the extraction efficiency of toxic gases, an on-site extraction experiment was conducted after presplitting blasting. The negative pressure in the main pipeline was set to -25. kPa, with a flow rate of 52.6 m³/min. Monitoring sensors were used to record the parameters of the main gas drainage pipeline. Figure 8 illustrates the variation in CO extraction concentration over time for the two different blasting schemes following deep-hole presplitting blasting.

From the data trends, both schemes exhibit a similar pattern of CO concentration variation over time: during the initial stage after blasting, the CO concentration rises

rapidly to a peak, followed by a sharp decline, and eventually stabilizes. However, a comparison of the two curves reveals that in Scheme 2, the CO concentration decreases more rapidly throughout the process, and the final stabilized CO concentration is significantly lower than in Scheme 1. Compared to Scheme 1, the blasting process in Scheme 2 results in more effective extraction and discharge of CO gas. The results indicate that using smaller-diameter boreholes ($\Phi 75$ mm) helps to reduce the radius of the crushed zone, enhance gas accumulation, and ultimately improve the efficiency of toxic gas extraction after blasting.

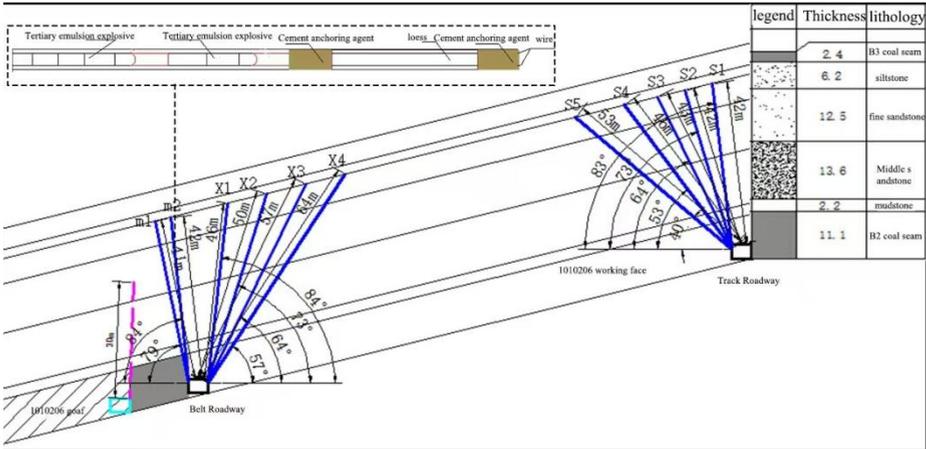


Fig. 6. Pre-splitting blasting profile of roof

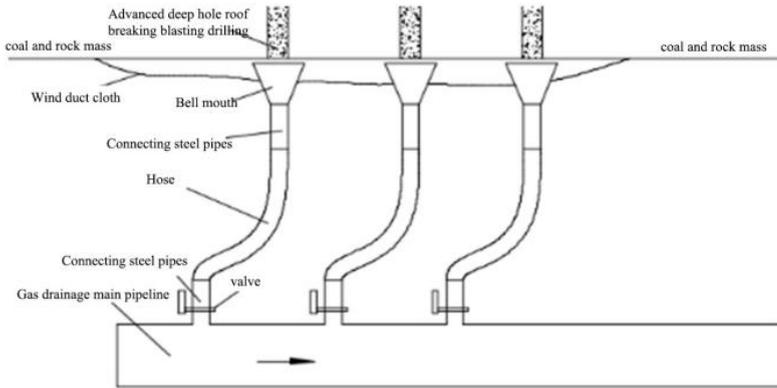


Fig. 7. schematic diagram of pre-splitting hole orifice drainage device

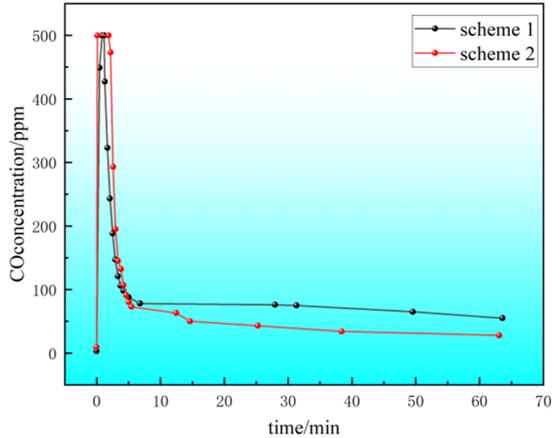


Fig. 8. Comparison of CO extraction effect

5 Conclusion

This paper, based on quasi-static and dynamic theories, develops a new mathematical model to calculate the displacement and porosity changes after blasting. The displacement and porosity variation patterns during the blasting process are derived, with calculations conducted using the Kuangou coal mine as an example. The following conclusions are drawn:

1. The displacement in the crushed zone decreases linearly, with the proportional coefficient being the ultimate strain, while the displacement in the fracture and elastic zones follows an inverse proportional power-law relationship. The power exponent is the attenuation coefficient of the rock stress wave and seismic wave. The radius of the crushed zone under the action of the blast shock wave is smaller than that under the action of explosive gases, while the radius of the fracture zone under the blast shock wave is larger than that under the action of explosive gases. The ratio of total displacement under the blast shock wave to that under the explosive gas effect is 1:2.19. The blast shock wave primarily leads to the formation of rock fractures, while the explosive gas effect is the main factor responsible for fracture expansion.
2. Based on the displacement pattern, the porosity variation pattern is derived. In the crushed zone, the porosity under the action of explosive gases is greater than that under the action of blast shock waves. In the fracture and elastic zones, the blast shock wave causes a reduction in rock porosity. After the blast shock wave phase, the increase in displacement caused by the explosive gases leads to an increase in porosity, though still lower than the initial porosity. The primary changes in rock porosity after blasting occur during the explosive gas phase.
3. Toxic and harmful gases generated after blasting are mainly concentrated in the blast cavity and the fracture spaces of the crushed zone, while the fissure zone contains relatively fewer fractures. Based on the distribution characteristics of fracture

spaces, minimizing the radius of the crushed zone is essential to enhance the efficient accumulation of post-blast toxic gases and facilitate their extraction. By optimizing blasting parameters such as borehole diameter, the extraction efficiency of toxic gases can be significantly improved, providing theoretical support and practical guidance for gas management in engineering blasting.

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