

# Numerical Simulation of the Relationship between the Width of Destressed Zone and Blasthole Depth

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## Abstract

Overstress in the surrounding rock of the roadway is a key reason that causes failures of deep roadways. Destressing blasting is one of the promising techniques that could improve the supporting quality. If the depth of the pressure relief blast hole is too shallow, the surrounding rock of the roadway will be broken or even collapsed. If the pressure relief blast hole is too deep, the pressure relief area will be located in the deep part of the surrounding rock of the roadway, which cannot achieve the purpose of releasing the stress in the shallow part of the surrounding rock and cause waste of the blast hole. The width or range of the pressure relief area should just fall in the high stress area of the surrounding rock of the roadway, so the pressure relief blast hole should have a reasonable depth. In order to quantitatively describe the relationship between borehole depth and the width of the stress relief zone, numerical simulations were carried out in ANSYS according to different borehole depths. The results show that the optimal destressing effect is achieved when borehole depth is 4 m. Peak stress of  $\sigma_\theta$  and  $\sigma_\gamma$  is significantly reduced by 30.51% and 49.07% after blasting. Meanwhile, the high-stress area shifts about 4.8 m from the roadside to the depth of surrounding rock, thus a 3.8 m wide stress relief zone is formed around the roadside, thus, the aim of quantizing the effects of destress blasting is achieved.

## Keywords

Rock Burst, Deep Roadway Supporting, Width of Stress Relief Zone, Destress Blasting, Numerical Simulation

## 1. Introduction

With the increase of mining depth, traditional means have been unable to solve

the problems of deep roadway supporting [1], thus roadway supporting is confronted with serious challenges. Destress blasting, the main method widely used for the control and prevention of pressure bump, is an active approach to lower the frequency of rock burst [2]-[13]. In order to reduce the difficulties of deep roadway supporting and enhance the quality of supporting, this paper adopts destress blasting to improve the stress state of shallow surrounding rock and lower its stress level.

Regarding research on deep roadway supporting, theoretical analysis, numerical modeling, and field monitoring methods have been utilized to study the effect of destress blasting. The small deflection theory of elastic thin plate and numerical simulation has been used by Zhao S.K. *et al.* [14] to analyze the roadway floor stress condition, it has been found that the mining horizontal stress is the key reason for floor heave, when the position of blasting holes is in the middle of the floor and roadway center line, the prevention effect gets more apparent. Tian and Jing's research [15] utilizes the theory of confined blasting to systematically analyzes how destress blasting in a soft-rock tunnel can relieve pressure in the rock and its influencing factors, it shows that destress blasting hardens soft rock and transfers geo-stress to the depth of the surrounding rock, their research also points out that the width of pressure released zone is the key to evaluate the blasting effect, and the width of pressure released zone is also closely related to the depth of blast holes. In Chen *et al.*'s research [16], the destress tunnel model was studied using holographic static photo-elastic experimental system in different surrounded stress when blasting occurred in tunnel's sides, it shows destress blasting betters the stress state of surrounding rocks. Researches of Gao *et al.* [17] and Zhang *et al.* [18] present that destress blasting reduces the stress of the surrounding rock which helps maintain the stability and safety of the high stressed surrounding rock. Both Zhang Ping's [19] and Zhao Gan's [20] researches perform experiments by adopting the way of bolting and destress blasting to repair the roadway, their experiments indicate that destress blasting improves the stress state of the surrounding rock and reduces the stress acting on the supporting structure. In Guo's and Wang's study [21], the surrounding rock stress is monitored and the supporting performance before and after blasting is analyzed, it shows destress blasting transfers the peak stress and changes the distributing regulation of surrounding rock stress field.

At present, destress blasting has become an essential means which is widely applied in practice among the deep roadway supporting for its effectiveness in increasing the roadway supporting quality. However, a great number of practical applications are still based on experience, thus how to make the destress blasting optimum is not sure. There is still no quantitative concept of some problems such as how much can destress blasting reduce the stress level of surrounding rock, how widely can destress blasting form the destressed zone in the shallow surrounding rock and how far can destress blasting transfer the high stress to the depth of rock away from laneway's side.

In order to obtain the quantitative conclusion of the effect of unloading blast-

ing in the deep tunnel, further the understanding of the nature of destress blasting and provide the professional guidance, this paper investigates relationships between the changing depth of blast holes and the effect of unloading blasting by using numerical simulation method.

## 2. Numerical Models and Parameters

### 2.1. Yield Criterion

In this paper, ANSYS is adopted to simulate the destress blasting's effect on roadway surrounding rock. In order to set up the numerical simulation, firstly, the element type of roadway rocks should be confirmed. Considering deformation characteristics of roadway surrounding rock, SOLID65 is selected for its properties of tension crack, crush, plastic deformation and creep.

Secondly, yield criterion of roadway surrounding rock should be confirmed. Present yield criteria for geotechnical materials roughly includes Von Mises yield criterion, Mohr-Coulomb yield criterion, Drucker-Prager (D-P) criterion *et al.* Among them, D-P criterion can describe the deformable features of rock and concrete more accurately [22]. Thus, D-P yield criterion is selected in the simulation to judge when roadway-surrounding rock starts to yield under the complex stress condition. Materials using the D-P yield criterion are referred to as D-P materials for short.

In the data table of ANSYS's options for D-P material, numerical values of cohesion  $C$ , internal friction angle  $\varphi$ , dilatancy angle  $\varphi_f$  need to be typed in. Dilatancy angle  $\varphi_f$  is used to control the size of volume expansion. The compacted granular material will dilate when it is in shear. If  $\varphi_f = 0$ , the volume will not dilate, if  $\varphi_f = \varphi$ , all materials' volume will dilate seriously. In general,  $\varphi_f = 0$  is a conservative approach.

The compressive yield strength of D-P material is much higher than its tensile yield strength. When uniaxial compressive stress and uniaxial tensile stress are known, internal friction angle  $\varphi$  and cohesion  $C$  can be expressed as:

$$\varphi = \sin^{-1} \left( \frac{3\sqrt{3}\eta}{2 + \sqrt{3}\eta} \right) \quad (1)$$

$$C = \frac{\sigma_y \sqrt{3} (3 - \sin \varphi)}{6 \cos \varphi} \quad (2)$$

The relationship between  $\eta$ ,  $\sigma_y$  and compressive stress, tensile stress are as follows:

$$\eta = \frac{\sigma_c - \sigma_t}{\sqrt{3}(\sigma_c + \sigma_t)} \quad (3)$$

$$\sigma_y = \frac{2\sigma_c \sigma_t}{\sqrt{3}(\sigma_c + \sigma_t)} \quad (4)$$

For the D-P model, its equivalent stress ( $\sigma_e$ ) formula is:

$$\sigma_e = 3\xi\sigma_m + \left[ \frac{1}{2} \{S\}^T [M] \{S\} \right]^{1/2} \quad (5)$$

where  $\{S\}$  is deviatoric stress.  $[M]$  is determined according to the following equation of modified yield criterion which considering the effect of mean stress  $\sigma_m$ . This modified yield criterion can be used to determine whether the rock is in an elastic state or a plastic state.

$$F = 3\xi\sigma_m + \left[ \frac{1}{2} \{S\} [M] \{S\} \right]^{1/2} - \frac{6C \cos \varphi}{\sqrt{3}(3 - \sin \varphi)} = 0 \quad (6)$$

Mean stress  $\sigma_m$  is determined according to:

$$\sigma_m = (\sigma_x + \sigma_y + \sigma_z) / 3 \quad (7)$$

Material constant  $\xi$  is determined according to:

$$\xi = \frac{2 \sin \varphi}{\sqrt{3}(3 - \sin \varphi)} \quad (8)$$

## 2.2. Basic Hypothesis

The stress condition of roadway surrounding rock under blasting is extremely complicated. It is necessary to simplify the numerical model appropriately so that the key problem can be studied.

Thus following basic hypotheses are proposed:

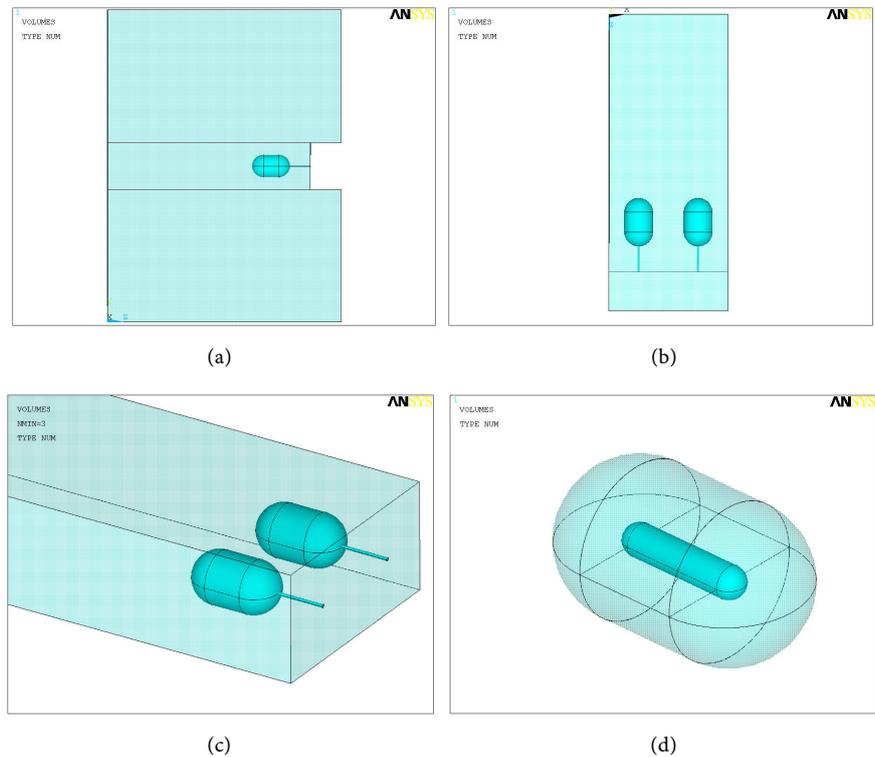
- 1) The burial depth of roadway is 800 m, and the underground stress field is under uniform loading.
- 2) The roadway is treated as a plane strain problem for its length is longer than its span.
- 3) Roadway surrounding rock is modeled as isotropic homogeneous continuous medium.
- 4) The effect of factors like deflection rate, temperature to stress and strain is ignored, and the time effect of resilience and creep is also ignored.

## 2.3. Calculation Modeling

In order to study the deformation law of roadway surrounding rock after blasting, the cross section of roadway is set as rectangular whose size is 4 m × 3 m. The maximum dimension of calculation model is about 5 times larger than the roadway width. According to the symmetry, half of the roadway is used to establish the calculation model. The size of model plane is 20 m × 15 m, the thickness of model is determined according to the simulation scheme. The element type of rock is SOLID65. The blasting hole is perpendicular to roadside. It is 1.5 m away from roadway floor and is arranged uniformly along the roadway. The blast hole adopts non-coupling charging structure. The numerical simulation model is shown in **Figure 1**

## 2.4. Parameters of Boundary Conditions and Mechanical Models

Boundary conditions are applied to the numerical simulation according to stress



**Figure 1.** Schematic diagram of numerical model. (a) Front view; (b) Top view; (c) Orthographic view of the damage zone; (d) Smash zone and fractured zone.

and displacement. All boundaries including the left boundary, the right boundary, the front boundary and the back boundary of the model are single constraint. Displacement constraint applied to the model is horizontal direction. The bottom of model is set as multiconstrained boundary. Both of the horizontal displacement and vertical displacement of boundary nodes are all zero. According to the buried depth of roadway and Heim's Hypothesis, the load applied to the top of model is overburden stress.

Surrounding rock's properties and mechanical parameters adopt the datum from the gate road of fully mechanized face in one mine (Table 1). Destress blasting zone's weakening method is based on the research [23]. Safety explosive, whose density is  $1000 \text{ kg/m}^3$ , detonation velocity is  $3500 \text{ m/s}$ , is adopted in the simulation.

## 2.5. Numerical Simulation

Factors influencing the pressure relief effect of blasting include rock parameters, blasting parameters and explosive parameters etc. To simplify the simulation, the surrounding rock conditions of the roadway (Table 1) and explosive parameters are kept unchanged. Under certain conditions of borehole diameter, charge length, borehole spacing and decouple coefficient, changing the hole depth to explore the relationship between hole depth and the size of released range. The numerical simulation scheme determined by the condition above is shown in Table 2.

**Table 1.** Mechanical parameters of rocks.

Position	Lithology	$E$ (Gpa)	$\mu$	$\rho$ (kg/m <sup>3</sup> )	$C$ (MPa)	$\varphi$ (°)
Roof	Sandstone	15.5	0.26	2450	3.6	25
Sidewalls	Coal	7.4	0.23	2210	2.5	20
Floor	Mudstone	5.3	0.21	2420	2.2	20
Smash zone	Coal	0.8	0.25	2210	1.5	16
Fractured zone	Coal	1.48	0.24	2210	1.9	18
Stemming	Clay	0.7	0.28	2130	1.2	15

**Table 2.** Numerical simulation scheme.

Hole Depth/m	Hole Diameter/mm	Decoupling Coefficient	Charge Length/m	Hole Spacing/m
4	50	1.2	2	3
5	50	1.2	2	3
6	50	1.2	2	3
7	50	1.2	2	3
8	50	1.2	2	3

To facilitate analysis and comparison, different models are numbered according to schemes and parameters of numerical simulation. Numbering of numerical models are A4, A5, A6, A7, A8, where 4, 5, 6, 7, 8(m) means the hole depth.

## 2.6. Path Extraction of Modeling Data

To extract the data that can reflect the stress and convergence deformation law of roadway surrounding rock before and after the destressing blasting, two analysis paths were set, and 65 monitoring points were arranged on each path.

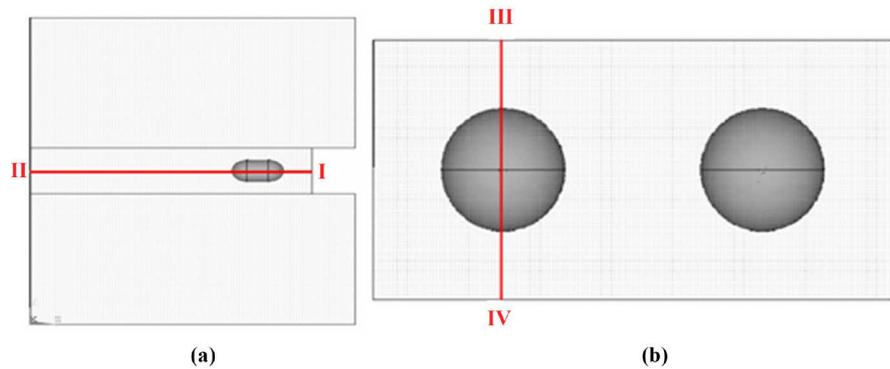
Path 1, is a horizontal section line along the middle of roadside shown in **Figure 2(a)**, and is used to monitor the stress change from the surface of the roadway to a depth of 13m of the surrounding rock. The tangential stress, and Mises stress of surrounding rock are extracted and analyzed. For sidewall, tangential stress  $\sigma_{\theta}$  is  $\sigma_y$ , radial stress  $\sigma_r$  is  $\sigma_x$ .

Path 2, as shown in **Figure 2(b)**, is a vertical section line which is perpendicular to Path 1, and is used to monitor and extract the deformation of the surrounding rock on roadway surface from the corner point of roadway roof to the corner point of roadway floor.

By comparing the deformation of roadway sides and surface surrounding rock before and after destress blasting, stress map and displacement map of roadway surrounding rock under different pressure relief parameters are drawn, and the variation law of each data is analyzed. Thus, the internal relationship between each blasting parameter and blasting pressure relief effect is determined, and the purpose of guiding the on-site destress blasting construction has achieved.

## 3. Results and Discussions

According to the simulation scheme in **Table 2**, the simulation process involves



**Figure 2.** Data analysis paths. (a) Path 1; (b) Path 2.

five factors: hole depth, hole diameter, decoupling coefficient, charge length and hole spacing. With different hole depths,  $\sigma_\theta$ ,  $\sigma_\gamma$  and deformation of surface surrounding rock are extracted from each model. Each data has 65 monitoring points.

### 3.1. Analysis of Blasting Pressure Relief Effect and Pressure Relief Range

When the hole depth is 4m, the hole diameter is 50 mm, the charge length is 2 m, the decoupling coefficient is 1.2 and the hole spacing is 3 m, Stress layout of side walls before and after destress blasting are shown in **Figure 3**.

Following analyses are concluded from **Figure 3**:

1) Before the blasting, when  $r = 2.0$  m,  $\sigma_\theta$  reaches a maximum of 39.54 MPa. When  $r > 2.0$  m,  $\sigma_\theta$  decreases gradually to 22.61 Mpa then tends to be stable as  $r$  increases. After the blasting,  $\sigma_\theta$  exhibits a bimodal distribution, the first peak value is 27.48MPa when  $r = 1.0$  m. the second peak value is 31.07 MPa when  $r = 4.8$  m.  $\sigma_\theta$  is reduced from 39.54 MPa to 27.47 MPa which unloading efficiency is 30.51%.

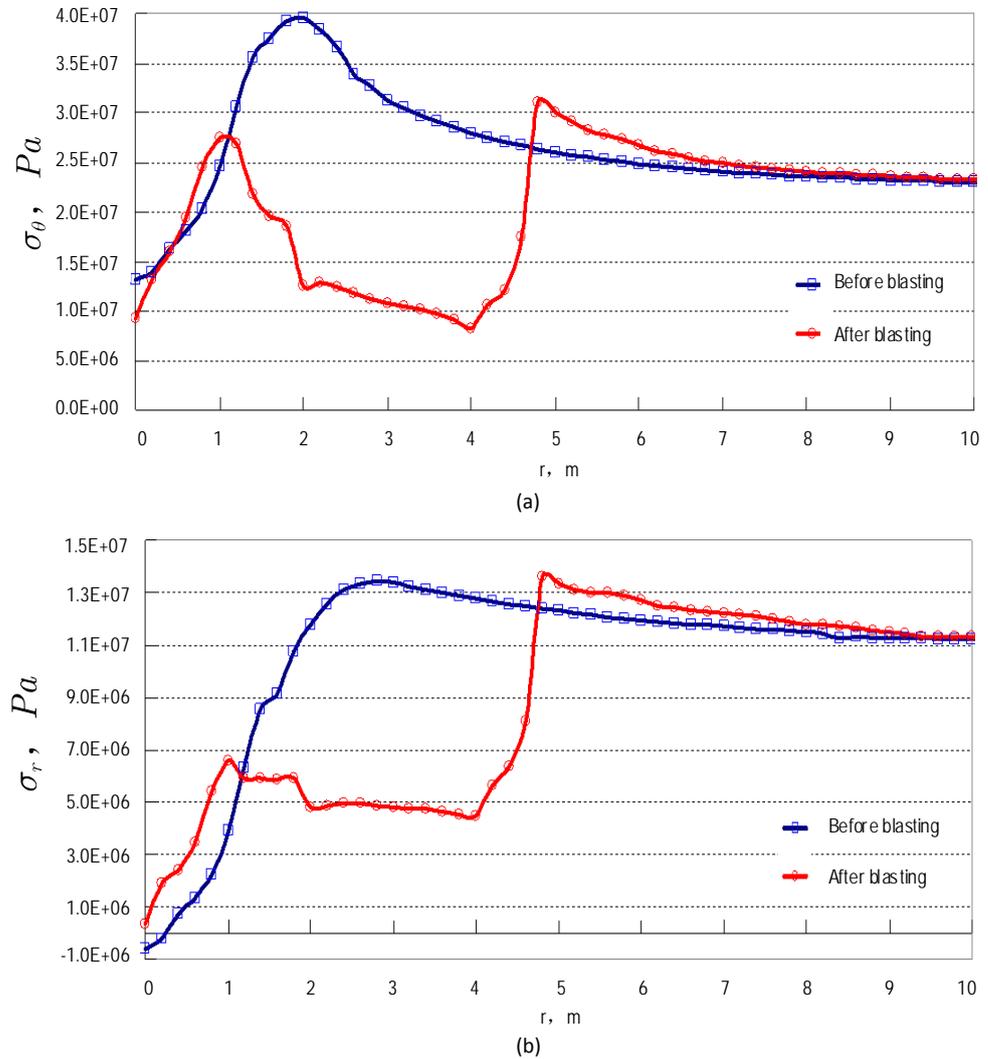
2) Before the blasting, when  $r = 2.8$  m,  $\sigma_\gamma$  reaches a maximum of 13.45 MPa. After the blasting,  $\sigma_\gamma$  also exhibits a bimodal distribution, the first peak value is 6.57 MPa when  $r = 1.0$  m. The second peak value is 13.60 MPa when  $r = 4.8$  m.  $\sigma_\gamma$  is reduced from 13.45 MPa to 6.85 MPa which unloading efficiency is 49.07%.

3) When  $r$  is between 1.0 m and 4.8 m, both  $\sigma_\theta$  and  $\sigma_\gamma$  decrease dramatically after the blasting, thus, this zone is viewed as stress relief zone, and the width of stress relief zone is about 3.8 m.

4) After the blasting, the high stress zone shift from the zone of  $1.0 \text{ m} < r \leq 2.0$  m to the zone of  $r \geq 4.8$  m.

### 3.2. Analysis of the Relationship between Hole Depth and Destress Blasting Effect

According to the schemes in **Table 2**, stress distributions of models from A4 to A8 before and after the blasting are shown in **Figure 4**.



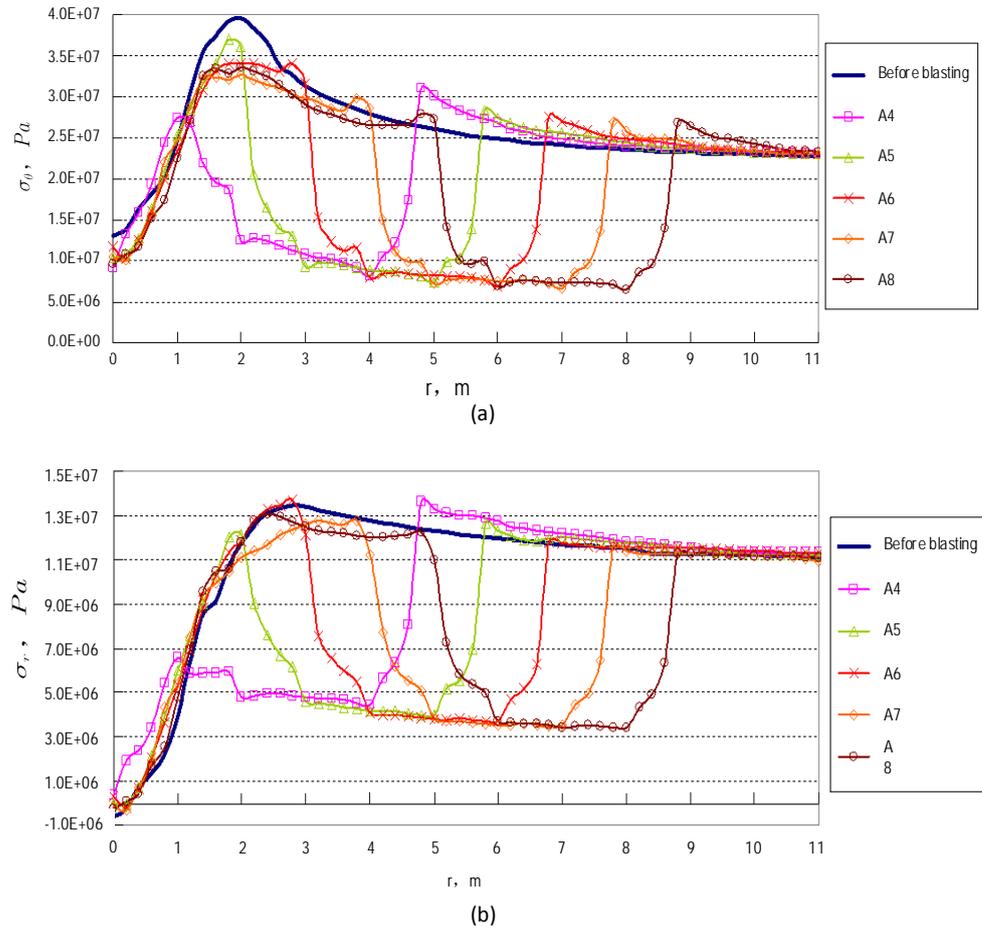
**Figure 3.** Stress layout of side walls before and after destress blasting. (a) Stress distribution of  $\sigma_{\theta}$ ; (b) Stress distribution of  $\sigma_{\gamma}$ .

Following analysis are concluded from **Figure 4**:

1) After the blasting, when the hole depth increases from 4 m to 8 m, peak stress's depth shifts from 4.8 m to 8.8 m, while the width of stress relief zone is still around 3.8 m. Peak stress  $\sigma_{\theta}$ 's reduce degree is 30.51%, 7.5%, 15.1%, 16.2% and 15.45%. Peak stress  $\sigma_{\gamma}$ 's reduce degree is 49.07%, 8.92%, 0%, 5.2% and 15.45%. Obviously, the optimal hole depth should be 4 m.

2) The width of high stress pillar in the shallow surrounding rocks increases from 1 m to 3 m as hole depth increases from 4 m to 8 m. It can be concluded that an over wide high stress zone is not good for the stability of roadway.

Therefore, the optimal destressing effect is achieved when the borehole depth is 4 m. The high-stress could be transferred to the deeper surrounding rock by increasing the blast hole depth but the pressure reduction effect of the surrounding rock in the shallow tunnel is not obvious, and this is not conducive to the stability of the tunnel.



**Figure 4.** Stress layout of side walls with different depths of blast holes before and after destress blasting. (a) Stress distribution of  $\sigma_\theta$  with different hole depths; (b) Stress distribution of  $\sigma_r$  with different hole depths.

### 4. Conclusions

In this paper, numerical simulations have been carried out to analyze the destress blasting effect in a quantitative manner, and multiple parameters have been taken into consideration. The following conclusions could be drawn:

- 1) The optimal blasting hole depth is 4 m. Under this setting,  $\sigma_\theta$ 's reduce degree can reach 49.07%,  $\sigma_r$ 's reduce degree can reduce 30.51%.
- 2) When the hole depth increases from 4 m to 8 m, peak stress's depth shifts from 4.8 m to 8.8 m, and a 3.8 m wide stress relief zone is formed.

Because there are many factors that affect the effect of pressure relief blasting, and because of the transient response, complexity and anisotropy of rock, it is undoubtedly more difficult to study the mechanism of pressure relief. The research in this paper is only a preliminary attempt in the quantitative research of blasting pressure relief technology, but also needs further research and exploration combined with field test. We have reason to believe that through unremitting efforts, we can find reliable theoretical support for the application of blasting pressure relief technology in deep roadway support.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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