Depressurizing boreholes for mitigating large deformation of the main entry

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Abstract
The main entries in longwall coal mine frequently encounter large deformation, depending on the stress environment. Depressurizing boreholes are applicable to reduce the large deformation; however, it is difficult to determine the proper parameters (diameter and spacing) for an effective implementation. This study aims to propose feasible design criteria for the quantification of those parameters. We first developed a rigorous numerical model, for a roadway in Zhangshuanglou coal mine, using the rock mechanical properties determined from extensive laboratory measurements and analyses. We then investigated the dependency of the stress transfer and roadway deformation on the ratio of borehole diameter and spacing (D/R and D/I). The symbols of D, R, and I represented the diameter, row spacing, and interspacing of the boreholes, respectively. We found that (a) D/R has to be between 1:6 and 1:2; and (b) D/I has to be between 1:6 and 1:4, for sufficient depressurization in the surrounding rocks. The optimized borehole diameter and spacing parameters were applied in the field where the deformation of roadway was significantly reduced. Finally, we proposed a criterion to determine those parameters of depressurization boreholes for application in other geological and mining conditions.

Keywords
depressurizing borehole, large deformation, longwall mining, roadway, stress transfer

1 INTRODUCTION

In Chinese coal mines, 70-80 percent of the annual roadway excavations are developed under the high-stress conditions which can be attributed to the geological abnormalities, the large burial depth, the strong abutment stresses, or the combination of those factors.1-3 The high-stress conditions often cause large deformation of the roadways, and in some cases, the convergence rate of roadway surfaces may reach up to 100 mm/d; therefore, significant efforts are routinely required to reconstruct the roadways.4,5 As a result, the cost of longwall mining is significantly increased and the production of coal is greatly restricted.1,6

Researchers have developed some techniques to improve the bearing capacities of the surrounding rocks and reduce the convergence of roadways developed under high-stress environment.1,7-11 Those techniques include the pumpable cribs, the strong rib/roof bolting, and many others summarized in Peng.12 However, field observations indicate that those techniques often have limited effects upon reducing the large deformation of surrounding rocks, primarily because the artificial reinforcement is far more uncompetitive to the
local stress environment. Alternatively, other researchers have proposed the concept of stress transfer to prevent the large deformation of the roadway under high-stress environment. The idea of this concept is to ease the local stress environment of a roadway by implementing some depressurizing techniques. For example, the roadway can be excavated in the depressurized zones after the neighboring longwall panel is retreated, or the depressurizing borehole, slotting, and joint-cutting can be implemented to actively transfer the high stresses away from the roadway surfaces. Successful applications of the stress transfer techniques have been reported in the literature for reducing the deformation of roadways under high-stress environment.

Among the depressurizing techniques, the boreholes are preferred in the coal mine industry due to the following reasons. First, it is operationally fast to drill the boreholes; thus, the productivity of longwall mining can be maintained. Other methods usually cause a notable delay of the retreat of longwall panels. Second, it is cost-effective to implement the depressurizing boreholes due to the improvement of the drilling equipment. Slotting and joint-cutting often cost more because of the difficulties of implementation and extensive labor work. For those reasons, the depressurizing boreholes have also been used to prevent rock-burst by releasing the stored elastic energy in rocks and improve the permeability of gassy seams by possibly decreasing the local stresses.

There are many challenges in parameterizing the boreholes, although successful case studies have been documented in the literature. This is because the borehole parameters not only affect the effectiveness of the stress transfer but also affect the structural integrity of the surrounding rocks. For instance, overspaced boreholes might damage the structural integrity of roadway, resulting in the instability issues. On the contrary, it is less effective to transfer the stresses when the boreholes are insufficiently spaced, which does not reduce the roadway deformation satisfactorily.

Researchers have summarized the five key parameters of the depressurizing boreholes, namely the borehole orientation, the timing of borehole drilling, the borehole length, the borehole diameter, and the borehole spacing. Researchers have reached consensus upon the design criteria for the first three parameters, which are summarized as follows.

1. The borehole orientation: The boreholes should be oriented in the direction perpendicular to the maximum principal stress. When the maximum principal stress lies in the vertical direction, major stress concentration occurs in ribs, not the roof/floor. Therefore, the depressurizing boreholes should be drilled in the horizontal directions in both ribs to release the stress concentration. In the other case where the maximum principal stress lies in the horizontal direction, the vertical boreholes need to be drilled in the roof and the floor. In a hydrostatic stress field, both types of boreholes are required.

2. The borehole length: The depressurizing boreholes are used to transfer the high stresses away from the roadway surfaces. Hence, the length of the borehole (L) should exceed the distance between the peak stress point and roadway surface L(σp). Based on extensive simulation and case studies, a quantitative criterion, 1 ≤ L/L(σp) ≤ 2, has been proposed to determine the optimal length of depressurizing boreholes.

3. The timing of borehole drilling: The rock properties, roadway deformation, and project deadlines should all be taken into consideration to determine the timing of borehole drilling. For the roadways developed in weak coal seams, large deformation usually initiates immediately after excavation. Therefore, predrilling of the boreholes is recommended. Predrilling of the boreholes would delay the development of roadway. Hence, for some roadways when the strength of surrounding rock is stronger, boreholes could be drilled upon the completion of roof and rib bolting. This allows the parallel operation of the roof/rib bolting and the boreholes implementation for a time-effective development of the roadway.

The above criteria have been successfully used to determine the orientation, the timing of drilling, and the length for the depressurizing boreholes in some Chinese coal mines. However, quantitative design criteria for the borehole diameter and the spacing have not been reached among researchers. The rule of thumb is that a greater spacing is preferred for a larger borehole diameter. Field applications, thus, mainly rely on the engineering analogy, which may cause significant uncertainties for the implementation of the depressurizing boreholes.

In the present study, we aim to propose design criteria for the proper diameter and spacing of depressurizing boreholes for effective stress transfer when roadways are excavated under high-stress environment. Note that the high-stress condition, in this study, mainly refers to the cases where roadways are buried at large depths (~1000 m). Under these conditions, the in situ stresses are usually greater than the bearing capacity of the shallow rock masses of the roadways. Figure 1 shows the workflow of the present study. A typical roadway with deep burial depth in Zhangshuanglou coal mine is selected as the engineering background. We first analyze the in situ stress and deformation characteristics of the roadway to determine the boreholes orientation as well as the timing of the drilling operations. The mechanical properties of the rock masses are then determined from the laboratory measurements and analyses, which enables us to develop a rigorous numerical model. The model enables us to locate the peak stress position around roadway such that
the lengths of the depressurizing boreholes can be determined based on previous studies.\textsuperscript{15} Afterward, an extensive numerical study is then conducted to investigate the effect of borehole diameter and spacing on the stress transfer and roadway deformation. Finally, we summarize the results of the numerical modeling and propose design criteria for the proper diameter and spacing of depressurizing boreholes for field applications.

\section{Laboratory Tests and Development of the Numerical Model}

\subsection{Engineering background}

The Zhangshuanglou coal mine, which located in Xuzhou mining area, eastern China, was selected for the case study. The tested roadway, namely −1000 m main roadway, was located in the No. 2 mining district (Figure 2). The total length of the roadway was 1300 m, and its burial depth was 1030 m. The roadway was not affected by the abutment stresses of longwall panels because there was no longwall panel prepared on both sides of the roadway. Sandy mudstone and mudstone were the main lithologies encountered by the roadway (Figure 2A). The roadway was excavated with an arched roof. The opening size was 4.8 m wide by 4.4 m high. Bolt-mesh-cable support was used for the roof and rib control. The primary support included the bolts of 800 × 800 mm spacing, while the secondarily support included cable bolts of 2.4 m spacing, which were also installed. The bolts were 22 mm in diameter and 2.4 m in length, and the cable bolts were 18.9 mm in diameter and 8.3 m in length. Kang et al\textsuperscript{27} measured the local in situ stresses. They reported that the maximum principal stress at −800 m and deeper lies in the vertical direction whose magnitude was approximately equal to the total weight of the overburden. The horizontal stress was equal to 0.8 times of the vertical stress.

During excavation, we installed three in-mine monitoring stations with 200 m spacing (green solid circles in Figure 2) to understand the deformation characteristics of the roadway. The measurements included roof-to-floor and rib-to-rib convergences, as shown in Figure 3A. Figure 3B shows the measured convergences during the development of the roadway. Each point is an average of the measurements at three monitoring stations. It was found that large deformations occurred in the initial 60 days after development, reaching up to 400 mm for the roof-to-floor convergence and 250 mm for the rib-to-rib convergence. Thereafter, the convergence rate was decreased, although the total deformations continued to accumulate. Figure 3C shows the profile of the deformed roadway after 90 days. For comparison, the initial opening was sketched.

Depressurizing boreholes were proposed to migrate the large deformation of the roadway by reducing the local stress concentration. The borehole orientation and the timing of drilling were determined based on the in situ stress conditions and the characteristics of the surface convergences of the roadway. Horizontal boreholes were drilled in both ribs because of the greater rib-to-rib convergence caused by the maximum principal stress in the vertical direction. The depressurizing boreholes were implemented after the installation of roof and rib bolting to speed up the roadway development. Besides, the determination of borehole lengths depends on the locations of the peak stress points in ribs, which will be discussed subsequently based on the numerical simulations.
2.2 | Model setup

The finite difference package, FLAC3D, was used for the numerical simulations. The model dimensions were 60 m × 40 m × 60 m, and 1,143,552 elements were included in the model (Figure 4). Note that we used Hypermesh to generate the complex meshes in the model, which were then transferred to FLAC3D. The meshes were refined around the boreholes, with 0.25 m as the smallest element size (see Figure 4A). All side boundaries were roller-constrained, and the bottom was fixed in vertical displacement. The upper boundary was subjected to even vertical stress of 25 MPa because the overburden depth of the roadway was 1030 m. The horizontal stress was applied as 0.8 times of the vertical stress based on the measurements of the in situ stresses.27 The opening size and supporting parameters of the roadway were consistent with those in the field. We did not include any longwall panels in the simulation, in order to be consistent with the field case.

2.3 | Strengths of the rock masses

In this section, we determine the mechanical properties of surrounding rocks of the roadway for numerical simulations.
For this purpose, we first conduct the triaxial measurements to determine the peak and postpeak properties of the intact core specimens. Here, it is important to quantify the postpeak properties of rocks because the large convergence of roadways is mainly attributed to the plastic deformation of the rocks. We then scale up the properties of the intact cores to those of the rock masses for the numerical simulation. Empirical model and field measurements are used for the properties upscaling.

We use the strain-softening Mohr-Coulomb model to quantify the peak and the postpeak properties of the rocks. As being documented in many studies, this model is characterized by the cohesion and friction angle for peak strengths and by the alternation of both properties for the postpeak behavior. The difficulty of using this model lies in quantifying the relations between rock properties (cohesion and friction angle) and the accumulation of the plastic strains. In this section, the following four steps were carried out to reveal the postpeak properties of rocks.

**Step 1:** We quantified the degradation of the rock mechanical properties of the intact cores as the plastic strains accumulate based on the triaxial measurements. The peak strengths of the rock specimens were measured under a confining pressure $\sigma_3$ of 25 MPa which was representative of the in situ stress of the roadway of interest. Afterward, the axial strain was increased until the axial stress degraded to certain percentages of the peak strength to obtain specimens with distinct damage states. The multiple failure state test method, proposed by Kovari et al., was used to determine the strength properties of the damaged specimens. The cohesion $c$ and the frictional angle $\varphi$ for each postfailure specimen were calculated based on the Mohr-Coulomb failure criterion, and both properties were related to the shear plastic strain ($\gamma_p$) which indicated the accumulation of the plastic strains. Finally, we observed the exponential degradation (Equations 1 and 2) of the cohesion and friction angle as the shear plastic strain was increased. Details of the triaxial tests can be found in our previous work.

$$c = 10.5952e^{-\gamma_p/0.00441} + 2.7157 \quad R^2 = 0.8168 \quad (1)$$

where $c$ is the cohesion of the intact core; $\varphi$ is the friction angle of the intact core; and $\gamma_p$ is the shear plastic strain of the intact core.

**Step 2:** For the implementation of the proposed model in the commercial numerical simulator, the shear plastic strain ($\gamma_p$) has to be related to the plastic strain ($\varepsilon^{ps}$) as defined in FLAC3D. Following the method of Alejano and Alonso, and Zhao and Cai, the accumulated plastic parameter $\varepsilon^{ps}$ in FLAC3D is related to the shear plastic strain $\gamma_p$ as:

$$\frac{\varepsilon^{ps}}{\gamma_p} = \sqrt{\frac{3}{6} (1 - \sin \psi)} \sqrt{1 + \sin \psi} \frac{1 + \sin \psi}{1 - \sin \psi} + \left(\frac{1 + \sin \psi}{1 - \sin \psi}\right)^2 \quad (3)$$

where $\psi$ is the dilation angle.

The average of the dilation angle ranges from 18.1 to 21.0 degrees for the tested core samples. Therefore, $\varepsilon^{ps}$ is related to $\gamma_p$ by substituting $\psi = \frac{18.1 + 21.0}{2} = 19.55^\circ$ into Equation (2). Combining Equations (1)-(3) allows us to implement the proposed model in FLAC3D as following:

$$c = 10.5952e^{-\varepsilon^{ps}/0.00225} + 2.7157 \quad (4)$$

$$\varphi = 12.2587e^{-\varepsilon^{ps}/0.00123} + 25.2349 \quad R^2 = 0.9105 \quad (2)$$

**Step 3:** Equations (4) and (5) describe the reduction of the postpeak strength of the intact rocks, which has to be converted to the relevant properties of the rock masses for the field-scale simulation. Here, we converted the strength properties of the intact rocks to those of the rock masses using the RocLab software, assuming $D = 0.5$, $GSI = 65$, and $m_i = 17$. The values of the $D$, $GSI$, and $m_i$ were determined by comparing the field observations of rock masses and the references given in the RocLab manual. Finally, we obtained the degradation of the strengths of rock masses (Table 1) for the field-scale simulation.

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**FIGURE 4** Finite difference (FLAC3D) model for the numerical simulations. The model dimensions were 60 m × 40 m × 60 m, and it included 1 143 552 elements. Figure (A) illustrates the cross section of one rib along the longitude direction of the roadway. The distance between the neighboring boreholes in the heading direction of roadway was defined as row spacing $R$, while that in the direction perpendicular to roof and floor was termed as interspacing $I$.
In-mine measurements were used to validate the proposed model of rock strength degradation. For comparison, another model using Mohr-Coulomb criterion without post-peak strength reduction of the rocks was also developed. The model results are shown in Figure 5, including the field measurements. The distributions of displacement, stress, and yield zone in the different depth of roadway surrounding rock were monitored by the multiple-position extensometer, borehole deformation gage, and imaging tools (see Figure 5), respectively.

The depths of the last induced cracks in the roof, the ribs, and the floor are used to sketch the profile of the induced cracked zone, which is compared with the results of the simulation (Figure 5A). The Mohr-Coulomb model, without consideration of strength degradation, significantly underestimates the yield zone. On the other hand, the strain-softening model produces the yield zone which matches the field measurements very well. This is because, in the strain-softening model, the yielding of the shallow domain provides relatively low confinement (due to postpeak strength degradation) to the neighbors. Thus, it is amenable for the yield zone to propagate further away from the roadway surface. Accompanied by the yielding of rocks around the roadway, their carrying capacities have declined, which results in the severe deformation around the roadway surface and the deep location of the peak stress in the surrounding rocks. As shown in Figure 5B,C, the strain-softening model captures both the stress profile in the ribs and the deformation around the roadway surface. Therefore, the proposed model has been successfully validated.

Both the simulation and field measurements show that the peak stress point is located at 6.5 m away from the rib line (Figure 5B). Based on Hou, the optimal length of boreholes is between 6.5 m and 13 m. The average value, 10 m, was selected in the numerical simulations for simplicity.

### 2.4 Evaluation indexes

Based on the previous discussion, the depressurizing boreholes are used to reduce the stress concentration around the roadway surface for migrating the large deformation. The stress transfer and deformation magnitude should be chosen as the indexes to evaluate the effectiveness of the boreholes. It is relatively straightforward to evaluate the surface convergence of roadway with and without the implementation of the boreholes. On the other hand, it is challenging to investigate the effectiveness of the stress transfer due to the complex stress distribution in the surrounding rocks.

For simplicity, we use the peak vertical stress in the ribs to evaluate the effect of the borehole parameters on the stress

| $e^{pr}$ | 0 | 0.001 | 0.002 | 0.003 | 0.004 | 0.005 | 0.006 | 0.007 | 0.008 | 0.009 | 0.010 | 0.020 | 0.050 |
|----------|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $c$ (MPa) | 3.32 | 2.75 | 2.40 | 2.15 | 1.98 | 1.85 | 1.78 | 1.71 | 1.68 | 1.66 | 1.64 | 1.61 | 1.61 |
| $\phi$ (°) | 35.24 | 31.65 | 29.00 | 26.98 | 25.49 | 24.36 | 23.58 | 23.04 | 22.66 | 22.42 | 22.26 | 21.97 | 21.97 |

**FIGURE 5** Comparison between the model predictions and the field measurements. Figure (A) Profile of the induced cracked zone, which is compared with the simulation results. Figure (B) Roadway deformations from the field observation and those of the simulations. Figure (C) Stress evolution in roadway ribs from the field measurement and simulations. The tools for the in-mine measurements are also presented.
transfer. In Section 2.1, we determined to drill horizontal boreholes in both ribs of the roadway. Hence, as shown in Figure 6, attention should be paid to the magnitude ($\sigma_p'$) and location ($L(\sigma_p')$) of the new peak stress upon the implementation of the depressurizing boreholes, while those factors without drilling the boreholes can be used as the references for comparison. In addition, the stress redistribution at the position of $L(\sigma_p')$ with boreholes should also be taken into account to evaluate the roadway stability because the stress magnitude in this position is related to the integrity of the surrounding rocks, which will be elaborated subsequently.

3 | NUMERICAL SIMULATION

In this section, we investigate the influence of borehole diameter and spacing on roadway stability based on the numerical simulations. An integrated modeling approach was used in the present study. As shown in Figure 4A, the boreholes were placed in the $Y$ direction with a minimum row spacing of 0.6 m, while each row ($Z$ direction) contains up to four horizontal boreholes with 0.6 m interspacing. Four possible values, 100 mm, 200 mm, 300 mm, and 400 mm (see Figure 4A), were considered for the borehole diameters. Subsequently, we study the effect of the three parameters (diameter, row spacing, or interspacing) on the roadway stability. Because spacing is closely related to diameter, we used the ratios of borehole diameter to row spacing ($D/R$) and to interspacing ($D/I$) to simplify the relationship between the three parameters. The model in Figure 4A allows us to consider different ratios of $D/R$ and $D/I$. Here, the simulations were mainly focused on the borehole diameter ($D$) and row spacing ($R$), while the borehole interspacing was considered as 1.2 m with $D/I = 1:4$. Six simulation plans with $D/R$ of 1:10, 1:8, 1:6, 1:4, 1:2, and 2:3 were considered. The simulation results without boreholes were regarded as a reference for comparison.

The effects of the different $D/R$ on the stress distribution and roadway deformation are shown in Figure 7A,B, respectively. In Figure 7A, the location of peak stress point $L(\sigma_p')$ moves away from the roadway surface with an increasing $D/R$. However, the location of the peak stress is not quite sensitive to the $D/R$ when it is between 1:10 and 1:6, although a slight reduction of peak stress values is observed. For the cases where $D/R \geq 1:6$, the increase of $D/R$ results in a significant increase of $L(\sigma_p')$, and the peak stress $\sigma_p'$ continues to decline. The stress values at the position of $L(\sigma_p)$ also decrease as the increase of $D/R$, especially when $D/R$ changes from 1:4 to 1:2. When $D/R$ changes from 1:2 to 2:3, there is almost no change for both $L(\sigma_p')$ and $\sigma_p'$. $L(\sigma_p')$ is slightly larger than the borehole length (10 m) which indicates the peak stress has been transferred to the end of the boreholes. However, the stress at the position of $L(\sigma_p)$ is decreased suddenly from 16.33 MPa to 9.24 MPa which represents a significant deterioration of the shallow surrounding rock. Therefore, it is reasonable to conclude that, in terms of stress transfer, the appropriate $D/R$ of the depressurizing boreholes should not be less than 1:6.

We also analyze the dependency of the roadway deformation on the $D/R$ of depressurizing boreholes. As shown in Figure 7B, when $D/R \geq 1:6$, the surface convergences of the roadway are smaller, comparing to the reference case where no boreholes are considered. When $D/R < 1:6$, the rib convergence is greater, although the roof-to-floor deformation is less, than that of the reference case. This phenomenon indicates that the rib deformations are not effectively controlled due to the insufficient spacing of the depressurizing boreholes. Moreover, the roof sag is increased suddenly from 350 mm to 470 mm, when $D/R$ is increased from 1:2 to 2:3. A possible explanation for this sudden increase of roof sag could be that the surrounding rocks in both ribs have lost support to the roof due to the severe damage caused by the overspacing of the boreholes. Hence, it is reasonable to conclude that, considering the roadway deformation, the preferred $D/R$ of the depressurizing boreholes should be between 1:6 and 1:2.

A reasonable row spacing of the boreholes for the tested roadway should maintain the value of $D/R$ between 1:6 and 1:2. When $D/R$ is within this range, the high stress around roadway could be effectively transferred to reduce the large deformation of roadway. For simplicity, we term this condition as sufficient depressurization. Moreover, the other cases of row spacing, that is, $D/R < 1:6$ and $D/R > 1:2$,
cause insufficient depressurization and overdepressurization, respectively. The stress distributions and the roadway deformation for all the three cases are summarized in Table 2.

The determined ratio of borehole diameter to row spacing ($D/R$) for the case of sufficient depressurization is relevant to the roadway with the given geological and mining conditions in the present study. Other geological and mining conditions may require different $D/R$ ratios for a sufficient depressurization. Subsequently, we propose an index to facilitate a case study with other geological and mining conditions. Comparing the distributions of the rib stress among cases in Table 2, we found different profiles of the stress distributions in $Y$ direction at the position of $L(\sigma_p)$. This stress profile was used to investigate the proper $D/R$ values for a sufficient depressurization.

**Figure 7** Effects of $D/R$ on the stress distribution in ribs and the surface deformation of roadway

**Table 2** Classification of the depressurization caused by the different $D/R$ ratios of the boreholes

| $D/R$                  | Example          | Distributions of stresses in ribs | Roadway deformation |
|------------------------|------------------|-----------------------------------|--------------------|
| Insufficient depressurization | $D/R < 1:6$      | $D/R = 1:10$                      |                    |
|                        |                  | ![Example](image1.png)             |                    |
| Sufficient depressurization | $1:6 \leq D/R \leq 1:2$ | $D/R = 1:3$                      |                    |
|                        |                  | ![Example](image2.png)             |                    |
| Overdepressurization    | $D/R > 1:2$      | $D/R = 2:3$                      |                    |
|                        |                  | ![Example](image3.png)             |                    |
The stress profiles (along the $Y$ direction in Figure 4A) between neighboring boreholes at the position of $L(\sigma_p)$ are shown in Figure 8, where different $D/R$ ratios are included. For an insufficient depressurization, this stress profile shows double peak points (Figure 8A,B) whose magnitudes are greater than the in situ stress of 25 MPa. The interplay between the neighboring boreholes occurs as the $D/R$ value is increasing because the stress profile eventually changes from the state of “double peak points” to the “single peak point.” For a sufficient depressurization, single peak point is observed in the stress profile between the neighboring boreholes, and its magnitude is greater than the in situ stress (Figure 8C-E). However, for the overdepressurization case (Figure 8F), the peak point of this stress profile is only 15 MPa, significantly lower than the in situ stress due to the excessive excavation of the depressurizing boreholes. Therefore, it is feasible to use stress profiles between neighboring boreholes at the position of $L(\sigma_p)$ for the determination of appropriate $D/R$ values. The reasonable $D/R$ value is characterized by two facts: (a) presence of single peak point of this stress profile; and (b) the peak value of this stress profile greater than the value of the in situ stress.

3.2 | Interspacing of the depressurizing boreholes

Here, we discuss the appropriate values of the ratio of borehole diameter to interspacing ($D/I$) for a sufficient depressurization. The borehole interspacing is different from the row spacing because the former is subjected to the restriction of the opening size. Here, four simulation plans with different interspacing were considered: (a) infinite interspacing (implementing borehole #2 only in Figure 4A); (b) $D/I$ of 1:6 (drilling boreholes #1 and #4); (c) $D/I$ of 1:4 (drilling boreholes #2 and #4); and (d) $D/I$ of 1:2 (drilling boreholes #1, #2, #3, and #4). The borehole diameter for all four cases was equal to 0.3 m, and the row spacing was fixed as 1.2 m ($D/R = 1:4$).

The stress distribution and roadway deformation with different $D/I$ values are shown in Figure 9A,B, respectively. Again, the case where no borehole is implemented is considered as the reference for comparison. For the infinite interspacing in Figure 9A, the peak stress is not transferred effectively, given the $L(\sigma_p)$ of 8 m; meanwhile, only a reduction of 5 MPa is observed for the peak stress value. Therefore, the roadway is still governed...
by the high stresses in the surrounding rocks because of the insufficient stress transfer. This interspacing also causes excessive roadway deformation, especially the rib convergence, as shown in Figure 9B. Therefore, the infinite interspacing results in insufficient depressurization based on the classification in Section 3.1. When \( D/I = 1:6 \) or \( 1:4 \), the peak stress is transferred to the end of the boreholes, and the stress at the position of \( L(\sigma_p) \) is decreased gradually with the increase of \( D/I \). The convergences of roadway are less than that of the reference case. These characteristics indicate that a sufficient depressurization is achieved for \( D/I \) of \( 1:6 \) or \( 1:4 \). As the \( D/I \) is increased to \( 1:2 \), there is almost no change in \( L(\sigma_p') \) and \( \sigma_p' \). However, the stress at the position of \( L(\sigma_p) \) is suddenly reduced from 26 MPa to 12.5 MPa. Moreover, the roof sag occurs is greater than that of the reference case. These characteristics indicate an overdepressurization when \( D/I \) is equal to \( 1:2 \), which could be attributed to the excessive borehole excavation. We summarized the depressurization with different \( D/I \) values in Table 3.

Here, we analyze the stress profile between neighboring boreholes in the \( Z \) direction (Figure 4) for further discussion of the \( D/I \) values. Figure 10 gives such stress profiles at the location of \( L(\sigma_p) \) when \( D/I \) is equal to \( 1:2 \), \( 1:4 \), or \( 1:6 \). For the sufficient depressurization where \( D/I \) is equal to \( 1:4 \) or \( 1:6 \), the stress profile is characterized by a single peak point whose value is greater than that of the in situ stress value. For the overdepressurization where \( D/I \) is equal to \( 1:2 \), the stress profile shows a much smaller peak value, comparing to the in situ stress value. This is mainly caused by the excessive excavation of the boreholes in ribs. Moreover, it is interesting to see the similar characteristics of the stress profiles between neighboring boreholes for the sufficient depressurization in the discussion of \( D/R \) (Figure 8) and \( D/I \) (Figure 10). Therefore, it is plausible to use the stress profiles at the location of \( L(\sigma_p) \) for the determination of appropriate row/interspacing of boreholes. Finally, it is important to emphasize that the present study is relevant to reduce the large deformation of main entries whose stability is mainly influenced by the high in situ stresses. In other words, the roadway instability problems caused by longwall abutment stresses, as documented in Ref.\(^{36,37} \) is beyond the scope of the present study.

**TABLE 3** Classification of the depressurization caused by the different \( D/I \) ratios of the boreholes

| Terms             | Ratio of borehole diameter to interspacing |
|-------------------|-------------------------------------------|
| Insufficient depressurization | \( D/I < 1:6 \)                          |
| Sufficient depressurization | \( 1:6 \leq D/I \leq 1:4 \)              |
| Overdepressurization    | \( D/I > 1:4 \)                           |

**FIGURE 10** Stress distribution between the neighboring boreholes at the position of \( L(\sigma_p) \) for different \( D/I \) values. The stress profiles are relevant to the vertical stress along \( Z \) direction (see Figure 4A).
Discussion of the borehole diameter and spacing

The borehole diameter and spacing are not independent parameters, as discussed previously. In reality, it is convenient to first determine the borehole diameter because it mainly depends on the availability of drillers. The spacing parameters of boreholes can be optimized once the borehole diameter is determined. The stress profile and its peak value between the neighboring boreholes at the location of $L(\sigma_p)$ can be used for the optimization. In detail, this stress profile should present a single peak whose value is greater than the in situ stress for the optimization of the spacing parameters of depressurizing boreholes. Therefore, sufficient depressurization could be achieved and the large deformation of the roadway can be reduced effectively.

FIELD APPLICATION

The determined parameters of the depressurizing boreholes were applied in the field. According to the mining conditions of the roadway of interest, the boreholes with lengths of 10 m were drilled horizontally in both ribs after the implementation of the roof and rib bolting. The existing driller of model ZL-4800 in the field site was used. This driller allowed us to drill boreholes with a diameter of 150 mm. Based on the established principals in Section 3, the spacing parameters of boreholes were determined as 0.9 m by 0.9 m to achieve a sufficient depressurization.

In order to minimize the disturbance of the borehole drilling to the supporting structures, the boreholes were implemented between the neighboring rows of bolts. Meanwhile, we slightly adjusted the parameters of roof/rib bolting for easier implementation of the depressurizing boreholes. The other bolting parameters remained the same as presented in Section 2.1. In order to control the floor heave, the bolts were installed at the floor corner and a concrete layer of 200 mm thick were constructed on the surface of the floor. Figure 11 illustrates the detailed parameters for the roof/rib bolting and the depressurizing boreholes.

The depressurizing boreholes were implemented as the new excavation was conducted (red lines in Figure 2). Figure 12 shows the results of the in-mine measurements. The deformation of the surrounding rocks is observed to increase rapidly in the 50 days after excavation. Afterward, the

![Figure 11](image1.png)

**FIGURE 11** Optimized parameters for the depressurizing boreholes and roof/rib bolting

![Figure 12](image2.png)

**FIGURE 12** Field measurements of the roadway deformation after the implementation of the depressurizing boreholes

1 – Rib-to-rib (without depressurizing boreholes)
2 – Roof-to-floor (without depressurizing boreholes)
3 – Roof-to-floor (with depressurizing boreholes)
4 – Rib-to-rib (with depressurizing boreholes).
deformation rate is decreased substantially. The roof-to-floor and rib-to-rib convergences are 200 mm and 130 mm, respectively, 100 days after the excavation of roadway. The roadway convergences are significantly less than those without the implementation of the depressurizing boreholes (curves 1 and 2 in Figure 12). Additionally, it is found that the rib deformation of the roadway, when employing the depressurizing boreholes, is reduced to 30% of the deformation without the implementation of the depressurizing boreholes. Therefore, the deformation of roadway has been effectively reduced when the depressurizing boreholes are employed (Figure 12A).

We have only considered the row-by-row design of the depressurizing boreholes in the present study. However, other patterns of the boreholes, for example, staggered or triangular layouts, may also be employed to reduce roadway convergence once the proposed design criterion is satisfied. Future study can be conducted to consider the staggered or triangular layouts of the boreholes because these patterns have the potential to reduce the drilling costs significantly.

5 | CONCLUSIONS

The objective of this study was to propose a deterministic approach of the depressurizing boreholes for deformation mitigation of a main entry subjected to high in situ stresses. For this purpose, major parameters of depressurizing boreholes were discussed and a rigorous numerical model was developed. The analyses were focused on the appropriate values of the diameter and spacing of boreholes, which were not extensively studied previously. We discussed the stress transfer and roadway deformation, using numerical simulations, to evaluate the effectiveness of the depressurizing boreholes. It was found that the proper diameter and spacing of boreholes could effectively reduce both the stress concentration in the surrounding rocks and the surface convergence of roadway. We suggested the appropriate values for $D/R$ (ratio of diameter to row spacing) and $D/I$ (ratio of diameter to interspacing) for the roadways discussed in this study. The ratios of $D/R$ and $D/I$ were considered, instead of the individual values of diameter and spacing, because these parameters were interdependent. Finally, the optimized borehole diameter and spacing parameters were applied in the field. The measurements showed that the large deformation of the roadway, caused by the high stresses, was greatly reduced after the implementation of the depressurizing boreholes.

The further analysis helped us to propose an approach for the determination of proper diameter and spacing of boreholes when roadways are subjected to other geological and mining conditions. The stress profile (along $Y$ direction) between the neighboring boreholes at the peak point in the $X$ direction (see Figure 2 for detailed directions) can be used for this purpose. It was found that the appropriate depressurization is achieved when this stress profile exhibits a single peak with its magnitude greater than the in situ stress values. With this characteristic of the stress profile, implementation of the boreholes could effectively transfer the stress concentration away from the opening without significantly deteriorating the structures of the surrounding rocks. Accordingly, the surface convergence of roadway can be greatly reduced. The absence of this characteristic of the stress profile indicates either an excessive depressurization where roadway deformation is enlarged or insufficient depressurization where large deformation remains. This finding could serve as a criterion for the design of depressurizing boreholes for a given geological and mining conditions.

The proposed criterion was successfully applied to the roadway under high in situ stress condition. The applicability of the criterion to other roadways, whose instability is mainly attributed to the retreat of longwall panels, needs further investigation. This is because longwall-affected roadways may experience different failure mechanism, comparing to the roadway failure caused by high in situ stress condition.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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