Numerical study on the multi-stage blasting in horizontal well to enhance the permeability of deep reservoir

Yuan Wei¹,², Hu Huihua³, Wang Anli⁴, Xu Jiang⁴, Wang Wei¹,², Niu Qinghe¹,² and Bai Bing⁵

¹School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, China; ²Hebei Technology and Innovation Center on Safe and Efficient Mining of Metal Mines, Shijiazhuang, China; ³Hunan Provincial Communications Planning, Survey and Design Institute, Changsha, Hunan, China; ⁴GuiZhou Water&Power Survey-Design Institute Co., Ltd, Guiyang, China; ⁵Chinese Academy of Sciences, Institute of Rock and Soil Mechanics, Wuhan, China

ABSTRACT
Blasting fracturing technique has developed into a most promising option replacing the hydraulic fracturing for enhancing the permeability of deep formation in the resource exploitation. At present, blasting-enhanced permeability mostly focus on the blasting-inducing fractures in vertical well. Thus, this paper emphatically studies the issues associated with the multi-stage blasting in horizontal well. In this work, a numerical rectangular-solid model consisting of 64000 elements has a size of 100×10×8 m (L×W×H) is established based on the finite-difference method to simulate a uranium resource reservoir in the Xinjiang Autonomous Regions, China. A horizontal well with the diameter of 20 cm and the length of 100.0 m is located at the center of this model. The shock wave resulted from the explosive detonation is simulated as a time-varying pressure applied to the wall of the well borehole. Four modes of the multi-stage blasting are investigated with the consideration of different in-situ stress conditions. The results show that multi-stage blasting has great effect on the rock damage and blasting-enhanced permeability, while the in-situ stress condition can not be an ignored factor in this affection. For relatively large compressive in-situ stress condition, 1-stage blasting is a recommended mode for improving the permeability of rock reservoir. However, for relatively small in-situ stress, the permeability of rock reservoir increase first and then decrease along with the increasing of subsections of multi-stage blasting. There must be an optimal mode of multi-stage to improving the permeability of rock reservoir.

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1. Introduction
Uranium is a very important strategic resource in the nuclear industry. The rapid growth of the utilization of nuclear energy leads to the sharply increasing demand for...
uranium resource in China. However, the exploration results of uranium resource reveal that more than seventy percent of uranium mines occur in the compact sandstone reservoir with extremely low permeability in China. Thus, improving the permeability of the reservoir is an extremely important way to enhance the exploitation efficiency of the uranium resource (Wang et al. 2016).

Hydraulic fracturing technique has been successfully applied to enhancing the productivity in oil, gas and other resource extraction areas since 1950s. However, experiences show that two obvious drawbacks of hydraulic fracturing can not be ignored: (1) the hydraulic fracturing process would lead to a huge amount of water consumption and impose a threat to the ground water resource, and (2) the fractures stimulated by the hydraulic pressure are limited to propagating only along the maximum stress orientation, which leaves a large area draining either inefficiently or not at all (Guo et al. 2014). Thus, blasting fracturing performs as a promising option to replacing the hydraulic fracturing in the well completion process. Researchers have gained a great deal of knowledge associated with the formation’s permeability improved by explosive blasting in the blasthole in the past several years. In summary, the previous main research contents could be classified into three aspects:

1. The shock wave, combined with the action of explosive gas pressure, perform a joint effect on the initiation and propagation of cracks in the reservoir. When the rock is located with surrounding constraints and has no free surface, there is no path way for the detonation gas leaking from the blasthole. Thus, the detonation gas would apply the quasi-static loading on the cracks with long duration (Saharan et al. 2006; Ozgur & Tugrul 2013). For examples, Olsson et al. (2002) have used lab tests to distinguish the effect of detonation gas and the shock wave on inducing cracks in the rock. It is found that the gas pressure only separates the already formed cracks and has no effect on the crack propagation. Cho et al. (2004) have studied the dynamic fracture process and gas flow through the fractures, and the results reveal that the detonation gas could considerably affect the production and growth of the cracks. Mohammadi and Pooladi (2012) have investigated the broken process of the solid stimulated by blasting, which shows that the detonation gas plays a positive role in enlarge the fracture networks. Zhu et al. (2013) have coupled the gas flow, rock deformation and damage to simulate the controlled blasting in the loosen coal seam, and the results show that both the shock wave and the gas pressure dominate the rock damage process. Lanari and Fakhimi (2015) have simulated the rock blasting with and without gas penetration into the cracks by virtue of finite element-discrete element-smoothed particle program, it is clarified that the shock wave formed most of the cracks, whereas the detonation gas mostly separated the rock fragments. Yuan et al. (2019) have investigated the contributions of shock wave and detonation gas to crack generation in deep rock without free surfaces, the results show that the shock wave plays a major role in crushing the rock near the blasthole, whereas the detonation gas further extends the fractures to increase the crushed area or separates the already formed rock fragments, which relies heavily on the additional stress caused by detonation gas.
2. Controlling blasting is a significant promising tool to enlarge the blasting effect. Recent researches have indicated that the decoupling charge structure could yield much more fractures using the same amount of explosive. Thus, seeking the decoupling coefficient is the key factor on the fracturing effects in rock blasting (Yi et al. 2016; Yuan et al. 2019). For examples, Lei et al. (2016) have conducted contrast tests of three shaped charge blasting groups with different charging coefficients to study the permeability improvement effects of blasting in coal seam. It is indicated that when the decoupling charge coefficient is 1.5, a stress wave with low dominant frequency produce the strongest stimulation effect. Yuan et al. (2018) have combined the PFC$^{2D}$ and UDEC to study the influence rules of decoupling charge on the improvement of permeability in sandstone reservoir. It is concluded that there must be an optimal decoupling coefficient for enhancing the reservoir’s permeability. Song et al. (2019) have studied the effect of decoupling coefficient on cumulative to improve the coal seam permeability. The test results show that decoupling charge could effectively improve the coal seam permeability and the optimal decoupling coefficient is recommended between 1.67 and 2.0. Yang et al. (2019) have used the model experiment to study the decoupling charge structure on the stress evolution in the rock blasting. The blasting stress attenuation index performs an initial increase and then a decrease with the increasing decoupling coefficient.

3. The tools for studying the blasting-enhancing permeability of the reservoir mainly focus on the numerical simulation method, including mesh-based (e.g., finite element method, FEM, extended finite element method, XFEM and discrete element method, DEM), mesh-free (e.g., cracking-particle methods and smoothed particle hydrodynamics, SPH) and coupling methods (e.g., FEM-DEM and DEM-SPH) (Gharehdash et al. 2020). For examples, Zhu and Zhao (2021) have presented a peridynamics-based computational approach for modelling blasting induced rock fractures, which is shown to capture reasonably well the plastic material failure surrounding the borehole as well as the tensile cracks on both radial and circumferential directions. Gharehdash et al. (2020) have used smoothed particle hydrodynamics (SPH) with Johnson Holmquist damage model to simulate the blast-induced fractures in Barre granite rock. Baranowski et al. have used the Johnson-Holmquist II (JH-2) model with parameters for a dolomite rock to simulate blast-induced rock fragmentation, and the numerical simulation results are compared and verified with the experimental tests. Fakhimi and Lanari (2014) have proposed a coupled DEM-SPH method to simulate the rock blasting, in which a bonded particle system is utilized to mimic the behaviour of rock and the particles interact at the contact points through normal and shear springs to simulate rock elasticity.

At present, most of the studies on the blasting-enhanced permeability of the reservoirs focus on the blasting fracturing in vertical well. Thus, in this paper, we devote to investigating the issues associated with multi-stage blasting in horizontal well to enhance the permeability of deep formation. A numerical rectangular-solid model with the size of $100 \times 10 \times 8$ m (Length $\times$ Width $\times$ Height) is used to simulate a
uranium resource reservoir in the Xinjiang Autonomous Regions, China, which is composed by 64000 finite-difference elements based on FLAC3D. A horizontal well with the diameter of 20.0 cm and the length of 100.0 m is located at the center of this model. The modes of the explosive stimulation (i.e. multi-stage blasting and simultaneous initiation in the entire horizontal well) have been studied with the consideration of different in-situ stress conditions. The core in this study is to provide a theoretical base and useful data for optimal design in the Uranium resource mining.

2. Numerical model

2.1. Mechanical parameters and mesh model

Bashibulake uranium deposit is a very important sandstone-type uranium deposit, which is located in Kashgar Sag in the west of China, Xinjiang Autonomous Regions, and consists of calcareous or siliceous cemented conglomerate. Geological survey results show that the main target ore bed is buried at a depth of 400 m and its average thickness is about 8.0 m. The dip angle of ore bed is nearly 3°~5°. In order to obtain the physical property parameters of ore bed, cylindrical rock samples are used for mechanical tests and wave velocity tests, as shown in Figure 1. Finally, all the concerned physical property parameters are shown in Table 1.

The uranium reservoir is simplified as a cuboid with the size of 100 × 10 × 8 m (Length × Width × Height). A hole with a length of 100 m and a diameter of 0.2 m is located at the centre of this cuboid, which works as a blasthole to enhance the permeability of uranium reservoir by blasting. The whole model is meshed as 64000
elements. The bottom of this model is subjected to normal displacement constraints, and the other five sides of the model are constrained by normal stress. The vertical stress \((v_z)\) applied on the top of the model is approximately equal to the gravity of overlying strata, i.e. \(v_z = 2760 \times 10 \times 400 = 11.04\) MPa. The horizontal stresses (i.e. \(v_x\) and \(v_y\)) applied on the lateral sides of the model are considered as tectonic stresses, which are determined according to their ratios to the vertical stress. Figure 2 shows the simplified model of the uranium reservoir.

### 2.2. Explosive loads

The decoupling charge structure is used in this study, and the uncoupled charge coefficient \((\zeta)\) is defined as:

\[
\zeta = \frac{d_b}{d_e}
\]

where \(d_b\) and \(d_e\) are diameters of the blasthole and the cartridge, respectively. In this study, \(d_b = 20\) cm and \(d_e = 12.5\) cm, thus, \(\zeta = 1.6\). Besides, the explosive density \(\rho_e = 1050\) kg/m\(^3\), the detonation velocity \(D_e = 4820\) m/s. According to the elastic wave motion theory, the peak value of explosive shock wave \((P_k)\) applied on the wall of the blasthole is given by (Henrych 1979; Fakhimi and Villegas 2007):

\[
P_k = \frac{1}{8} n \rho_e D_e \left(\frac{1}{\zeta}\right)^6
\]

where \(n\) is the amplification coefficient of the shock wave, which is generally deemed to be approximately equal to 8.0. Thus, \(P_k\) is calculated to be 1.45 GPa. To obtain the pressure-time profile of the explosive shock wave, the wave-shape function is needed. In this work, the wave-shape function to depict the pressure-history of the shock pressure on the blasthole wall is a general form of a pulse function, given by (Duvall 1953; Zhu et al. 2013):

\[
P_t = P_k \zeta (e^{-\alpha t} - e^{-\beta t})
\]

where \(P_t\) is the shock pressure at time \(t\), \(\alpha\) and \(\beta\) are constants, and \(\zeta\) is expressed as (Ma and An 2008; Zhu et al. 2013):

\[
\zeta = \frac{1}{e^{-\alpha t_r} - e^{-\beta t_r}}
\]

where \(t_r\) is the rising time of shock pressure to peak value and can be expressed as (Ma and An 2008; Zhu et al. 2013):

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**Table 1. Physical and mechanical parameters of specimens.**

| Density (g/cm\(^3\)) | Compressive strength (MPa) | Elasticity modulus (GPa) | Poisson’s ratio | P-wave velocity (m/s) |
|-----------------------|---------------------------|--------------------------|-----------------|----------------------|
| 2.76                  | 88.1                      | 12.9                     | 0.09            | 2359                 |

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For convenient representation of the rising and decaying phases, the ratio of $b$ to $a$ is 1.5, i.e. $b/a = 1.5$. The rising time $t_r$ is difficult to detect through the monitoring system, and it could be estimated according to the following equation (Yuan et al. 2019):

$$ t_r = \frac{1}{\beta - \alpha} \ln \left( \frac{\beta}{\alpha} \right) $$

(5)

where $C_r$ is the P-wave velocity propagating in the rock; $\rho_0$ is density of the rock; $u_x$ is velocity of the particles from the blasthole wall, which is thought to be 160 m/s in this study. Thus, the $t_r$ is calculated to be $3.16 \times 10^{-5}$ s. Once $t_r$ is determined, according to Eq. (3)~(5), the pressure-time history on the wall of the blasthole can be acquired, and then the shock pressure are considered as normal stress applied on the wall of the blasthole at each time step based on Eq. (3). In order to eliminate the interference of boundary reflection wave, transmitting boundary are set at the six sides of the uranium reservoir model. Figure 3 shows pressure-history on the wall of blasthole.

### 2.3. Failure criterion for the rock mass

Generalized Hoek-Brown (GHB) criterion is broadly accepted to depict the strongly nonlinear failure characteristics of the rock mass subjected high geostress and shock pressure (Erik 2012). The latest version of the GHB criterion is presented in 2002, and it has developed into one of the most broadly adopted failure criteria in rock engineering. The equation of the GHB criterion in principal stress space is given by (Hoek et al. 2002):

$$ t_r = \frac{3 P_k d_b - u_x d_b C_r \rho_0}{2 \rho_0 u_x C_r^2} $$

(6)
where $r_1$ and $r_3$ are the major and minor principal stresses of the rock mass at failure, respectively; $r_{ci}$ is the uniaxial compressive strength of the intact rock; $m_b$, $s$, and $a$ are empirical parameters, which could be acquired by (Erik 2012; Hoek et al. 2002; Yuan et al. 2020):

$$m_b = \exp \left( \frac{GSI-100}{28-14D} \right) m_i$$
$$s = \exp \left( \frac{GSI-100}{9-3D} \right)$$
$$a = 0.5 + \frac{1}{6} \left[ \exp \left( - \frac{GSI}{15} \right) - \exp \left( - \frac{20}{3} \right) \right]$$

where $m_i$ represents the rock type and hardness, which ranges from 1 to 40; GSI is geological strength index and used for depicting the structural features of the discontinuities in the rock mass, which generally varies from 5 (for a highly fractured and damaged rock mass) to 100 (for intact rock); $D$ reflects the impact of the rock mass subjected by stress disturbance, ranging from 0.0 (for undisturbed in situ rock mass) to 1.0 (for disturbed rock mass).

According to Eqs. (7) and (8), it can be concluded that $r_{ci}$, $m_b$, GSI and $D$ are the final input parameters of the $GHB$ criterion. Obviously, $r_{ci}$ and $m_i$ are the indexes to describe the characteristics of intact rock (not rock mass), which would not vary with the blasting time. However, for the different blasting time, the integrity and stress state of rock mass are not the same due to the impact of the shock wave, thus, GSI
and $D$ are not the constants during the whole blasting process and vary at each time step. In this study, $\sigma_{ei} = 88.1$ MPa (shown in Table 1), and $m_i$ is set to 18.0 referring to Hoek’s method. Next, we give a detailed calculation method for the GSI and $D$ at each blasting-time step.

Figure 4 shows two forms of the stress disturbance by means of stress circle in the ‘$\sigma$-$\tau$’ coordinate system. Stress circle $\circledcirc$ represents the stress state without disturbance. Stress circle $\circledast$ is levelly moved from stress circle $\circledcirc$, and it means that they have the same diameter. Stress circle $\circledast$ has the same center coordinates with stress circle $\circledcirc$, but it is originated from the enlargement of the stress circle $\circledcirc$. Thus, stress circle $\circledast$ and stress circle $\circledast$ are considered as two stress states after disturbance. In practice, the real stress disturbance is the combined actions of the parallel translation and the enlargement from the initial stress circle. Thus, we define a stress state index (SSI) to represent the stress state of a point in the rock mass after disturbance, which contains the center coordinates and radius of its stress circle, i.e.

$$SSI = \frac{(\sigma_1 + \sigma_3)}{2} \cdot \frac{(\sigma_1 - \sigma_3)}{2}$$

(9)

Once the stress circle has been changed from the initial stress state, we could use $D$ to estimate the degree of stress disturbance. As mentioned above, $D$ varies from 0.0 to 1.0, thus, we use an exponential function to define the calculation of $D$,

$$D = 1 - \exp\left(-\frac{SSI - SSI_0}{SSI_0}\right)$$

(10)

where $SSI_0$ means the stress state index before disturbance. According to Eq. (10), if there is no stress disturbance, $SSI = SSI_0$, thus, $D = 0.0$; if there is strong stress disturbance, $SSI$ approaches to infinity, thus, $D$ is close to 1.0.

Figure 5 shows the evolution curves of total stored elastic energy and total dissipated plastic work during the loading process. As shown in Figure 5, the whole process could be divided into three stages: stage I (elastic phase) → stage II (elastoplastic phase) → stage III (plastic phase). In the first stage, the rock is in a state of pure elasticity, and the external loading work ($W$) is totally converted into elastic strain energy ($W_e$) stored in the rock, i.e. $W = W_e$. In this stage, the rock has not been destroyed and its integrity has stayed the same as before. As the external load increases, the
rock begins to yield to failure and its integrity keeps decreasing. The external loading work is partially stored in the rock as elastic energy, and partially used for energy dissipation in plastic deformation ($W_p$). Thus, in the second stage, $W = W_e + W_p$. Once the rock is totally destroyed (stage III), its integrity is considered to be zero, and the external loading work is totally used for plastic work dissipation, i.e. $W = W_p$. In this study, GSI is an index affected by the damage degree of the rock, thus, it is considered that GSI changes with the variation of $W_p$, given by,

$$GSI = \begin{cases} 
GSI_0, & (W = W_e) \\
1 - \frac{W_p}{W}GSI_0, & (W = W_e + W_p) \\
0.0, & (W = W_p)
\end{cases}$$

(11)

where $GSI_0$ means the geological strength index without stress disturbance, and $GSI_0 = 100$ in this study. According to Eq. (10) and Eq. (11), $D$ and GSI for all the solid elements of the reservoir model could be updated at each blasting-time step by using FISH, which is a programming language embedded within FLAC$^{3D}$, enabling the user to define new variables and functions, as shown in Appendix.

In order to prove the validation of the presented method for describing the progressive failure of rock, we use the data from previous literature as a calibration object. Yuan et al. (2019) have combined the physical modelling experiments with the discrete element method to study the effect of water-decoupling charge structure on the attenuation of blasting stress. The model with the water-decoupling coefficients of 1.0 is selected from Yuan’s literature to calibrate the proposed method in this study. As described in the Yuan’s literature, the numerical model is simplified as a square with the size of 0.8 m $\times$ 0.8 m (Weight $\times$ Height), and one circular hole located at its center with the diameter of 0.0145 m. The physical and mechanical parameters of the solid elements in the model are listed as: density $= 2140$ kg/m$^3$, compressive strength $= 21.1$ MPa, elasticity modulus $= 19.94$ GPa, Poisson’s ratio $= 0.09$, $m_i = 12.0$, $GSI = 100$, $D = 0.0$. Figure 6 shows the failure area around the hole resulted from the...
discrete element method (PFC\textsuperscript{3D} code) and the presented method in this study (FLAC\textsuperscript{3D} code). As shown in Figure 6, the distribution range of the fractures resulted from the discrete element method is very close to the plastic zones range resulted from the presented method, which indicates that the presented method could properly simulate the progressive failure of rock under the action of blasting shock.

3. Multi-stage blasting in horizontal well

3.1. Working conditions of multi-stage blasting

In this study, the focuses are on the effect of multi-stage blasting to the improvement of permeability in the deep formation, as well as the influence of in-situ stress on the blasting fracturing. Thus, the different in-situ stress conditions for the rock blasting are shown in Table 2. For each case in the Table 2, four modes of multi-stage blasting are applied in the horizontal well, i.e. 1 stage, 5 stages, 10 stages and 20 stages. Figure 7 shows the schematic for the multi-stage blasting in the horizontal well using numerical simulation method, where 1 stage means the whole blasthole is initiated simultaneously, 5 stages, 10 stages and 20 stages mean the blasthole is divided into 5, 10 and 20 equal subsections to be sequentially initiated, respectively.

3.2. Analysis of the results

Suppose that the integrity index of the rock subjected blasting damage ($\psi$) is defined as the function of energy dissipation in plastic deformation ($W_p$) and external loading work ($W$), given by,

$$\psi = 1 - \frac{W_p}{W}$$

(12)

Based on Eq.(12), the $\psi$ of each element of the reservoir model could be calculated. Figures 8–10 show the results of $\psi$ after the action of blasting for Case 1 ~ Case 3. Note that all the figures in Figures 8–10 are sectional views, which are perpendicular to the blasthole and locate at the centre of the model of uranium

Figure 6. Failure area around the hole resulted from PFC\textsuperscript{3D} code and FLAC\textsuperscript{3D} code.
reservoir, i.e. the y-coordinate of the cross section is equal to 50 (y = 50). From Figures 8–10, we can find that the propagation of the rock damage induced by blasting has obvious directionality for Case 1 and Case 3 while this directionality is not so obvious for Case 2. More specially, the damage areas mainly extend along the z-axis in Case 1 (σ_x < σ_z) and along the x-axis in Case 3 (σ_z < σ_x), and the damage area grows roughly equally in both directions in Case 2 (σ_z = σ_x). Thus, it could be concluded that the stress anisotropy has significant influence on the propagation of the rock damage, which preferentially propagates along the maximum stress orientation. In addition, we can also find that the severely damaged area (blue area in Figures
Figure 9. Distribution of rock integrity for different modes of multi-stage blasting (Case 2).

Figure 10. Distribution of rock integrity for different modes of multi-stage blasting (Case 3).
8–10) in Case 1 is the largest, Case 2 follows, and Case 3 has the least severely damaged area. It is indicated that the magnitude of the in-situ stress can affect the extend of the damage area, and a greater in-situ stress would produce a smaller damage area.

It is no doubt that the stress disturbance stimulated by blasting wave is the essential cause of rock damage. In order to illustrate the effect of the in-situ stress on the production and propagation of the rock damage, we study the evolution rules of the stress disturbance during the whole blasting time. **Figure 11** shows the monitoring points arranged at the cross section, which is perpendicular to the blasthole with $y = 50$. The evolution curves of stress disturbance during the whole modelling process at different monitoring points are shown in **Figures 12–14**, in which the abscissa represents the number of calculating steps and the vertical abscissa represents the stress disturbance index. On the whole, we can find that the stress disturbances in $z$-direction are generally greater than those in $x$-direction in **Figure 12** (Case 1), however, the stress disturbances in $x$-direction are generally greater than those in $z$-direction in **Figure 14** (Case 3). In **Figure 13** (Case 2), the evolution curves in $x$-direction coincide exactly with those in $z$-direction. Through comparing the rock integrity distributions shown in **Figures 8–10** with the stress disturbance curves shown in **Figures 12–14**, it could be concluded that there is a significant correlation between the magnitude of stress disturbance and the propagation of rock damage area. To be specific, the rock damage preferentially propagates along the direction of the greatest stress disturbance, and a higher stress disturbance could promote the rock damage. Once the stress disturbance is isotropic, the rock damage extends nearly equally in all directions, producing a failure zone with no apparent directionality.

**Figure 15** shows the influence of the stress ration ($\sigma_z / \sigma_x$) on the axial length ratio of the failure area, where axial length ratio is the length of the failure zone in the $X$ direction ($X_{\text{length}}$) divided by the length of the failure zone in the $Z$ direction ($Z_{\text{length}}$). The relationship between the stress ration and the axial length ratio could be approximately expressed as a linear function,
In order to reveal the effect of multi-stage blasting on the rock damage, we could study the average rock integrity index in $x$-$z$ plane along the whole blasthole for different modes of the multi-stage blasting. The average rock integrity index in $x$-$z$ plane $\psi_{ave}(y)$ is defined as,

$$\psi_{ave}(y) = \frac{\sum \psi_i(y) \cdot V_i(y)}{\sum V_i(y)}$$ (14)

where $y$ is the $y$-coordinate of $x$-$z$ plane, $\psi_i(y)$ and $V_i(y)$ are the integrity index and the volume of the solid element, the $y$-coordinate of whose center is equal to $y$. Finally, the curves of $\psi_{ave}(y)$ along the whole blasthole for different modes of the multi-stage blasting are shown in Figures 16–18.

From Figures 16–18, we can find that the mode of multi-stage blasting has a strong impact on the results of rock integrity. Compared with multi-stage blasting,
1-stage blasting can produce a more uniform distribution of rock integrity along the whole blasthole. However, for the multi-stage blasting, the rock integrity would sharply decline at the intersection of the front and the back blasting sections, which performs as low-lying points in the curves of $\psi_{ave}(y)$.

In addition, the in-situ stress has a significant influence on the effect of multi-stage blasting. For Case 1 and Case 2, multi-stage blasting could promote the damage of the rock, i.e. the average rock integrity induced by 5-stages blasting, 10-stages blasting and 20-stages blasting is less than that resulted from 1-stage blasting. However, it does not mean that more segmented blasting will necessarily lead to more serious rock damage. Figures 16 and 17 show that the average rock integrity induced by 20-stages blasting is not greater than that resulted from 5-stages blasting and 10-stages blasting. For Case 3, there is not significant difference in rock damage from 1-stage blasting, 5-stages blasting and 10-stages blasting, and the 20-stages blasting produces the minimum rock damage. Thus, it is necessary to select appropriate multi-stage blasting mode for the different in-situ stress condition to lead to the maximum rock damage in engineering practice.
In order to estimate the effect of multi-stage blasting on enhancing the permeability, the following equation is used for calculating the permeability of uranium reservoir after blasting, given by (Taron et al. 2009; Cappa and Rutqvist 2011):

Figure 14. Evolution curves of stress disturbance during the whole modelling process at different monitoring points (Case 3).

Figure 15. The influence of the stress ration on the axial length ration of the failure area.

In order to estimate the effect of multi-stage blasting on enhancing the permeability, the following equation is used for calculating the permeability of uranium reservoir after blasting, given by (Taron et al. 2009; Cappa and Rutqvist 2011):
\[ f = \frac{k_i}{k_{18/C19}} \times \frac{1}{C0} \times \left( \frac{1}{C0} / \phi_i \right) \]  

where \( f \) means the enhancement coefficient of the permeability induced by blasting; \( k_i \) and \( \phi_i \) are the initial permeability and initial porosity of the uranium reservoir before blasting, respectively; \( k \) and \( \phi \) are the permeability and porosity of the uranium reservoir after blasting, respectively. \( \phi \) could be acquired by (Taron et al. 2009; Cappa and Rutqvist 2011):

\[ \phi = 1 - (1 - \phi_i) \exp (-\varepsilon_v) \]  

where \( \varepsilon_v \) is volumetric strain and \( \phi_i \) is equal to 0.1. According to Eq.(15) and Eq.(16), we could calculate the \( \zeta \) of each element of the reservoir model. Finally, the average enhancement coefficient of the permeability \( \zeta_{ave}(y) \) in \( x-z \) plane could be calculated similarly to defining the \( \psi_{ave}(y) \),

\[ \zeta_{ave}(y) = \frac{\sum \zeta_i(y)V_i(y)}{\sum V_i(y)} \]
where $y$ is the $y$-coordinate of $x$-$z$ plane, $\zeta_i(y)$ and $V_i(y)$ are the enhancement coefficient of the permeability and the volume of the solid element, the $y$-coordinate of whose center is equal to $y$. Thus, the curves of $\zeta_{ave}(y)$ along the whole blasthole for different modes of the multi-stage blasting are shown in Figures 19–21.

From Figures 19–21, we can find several characteristics of the curves of $\zeta_{ave}(y)$ very similar to those in the Figures 16–18:

a. Multi-stage blasting can also significantly affect the results of the blasting-enhanced permeability, and the in-situ stress condition is also not negligible factor in this affection.

b. The distribution of blasting-enhanced permeability along the whole blasthole is much more uniform from 1-stage blasting than that from the multi-stage blasting. For the multi-stage blasting, i.e. 5 stages, 10 stages and 20 stages, the curves of $\zeta_{ave}(y)$ have peak points at the intersection of the front and the back blasting sections.

c. For Case 1 and Case 2, the enhanced permeability resulted from multi-stage blasting is obviously greater than that induced by 1-stage blasting, and the maximum enhanced permeability is induced by 10-stages blasting rather than 20-stages blasting. For Case 3, the maximum enhanced permeability is induced by
1-stage blasting, and a more segmented blasting would lead to a smaller enhanced permeability.

Thus, the results indicate that an obvious correlation appears between the $\psi_{ave}(y)$ and the $\zeta_{ave}(y)$. In practice, enhancing the permeability of the rock reservoir by multi-stage blasting should consider the different in-situ stress conditions. When the in-situ stress is relatively small, multi-stage blasting is superior to 1-stage blasting to improve the reservoir's permeability. As the number of multi-stage blasting increases, the enhancement coefficient of the permeability increases first and then decreases, and there must be an optimal multi-stage blasting for enhancing the permeability. Just like Case 1 and Case 2 with relative small in-situ stress in this study, 10-stage blasting is the optimal mode of multi-stage blasting. When the in-situ stress is relatively large just like Case 3, 1-stage blasting is superior to multi-stage blasting to improve the reservoir’s permeability, and 1-stage blasting is the optimal mode of multi-stage blasting.

4. Conclusions

This paper has studied the effect of multi-stage blasting in horizontal well on the enhanced permeability of the rock reservoir. In this study, four modes of multi-stage blasting with the consideration of different in-situ stress conditions have been discussed. Through comprehensively analyzing the distribution of rock damage and the enhanced coefficient of permeability, the following conclusions can be acquired:

a. The stress disturbance stimulated by blasting wave is the essential cause of rock damage. The in-situ stress anisotropy leads to the stress disturbance having directionality, thus, the rock damage also performs strongly directionality and preferentially propagate along the direction of the maximum stress disturbance. In addition, the stress disturbance has significant influence on the area of the rock damage, and a higher stress disturbance could promote the rock damage.

b. Multi-stage blasting can significantly affect the results of rock damage and the blasting-enhanced permeability. Note that the in-situ stress condition is also not negligible factor in this affection. For relative small compressive in-situ stress condition, the degree of rock damage and the permeability of rock reservoir
increase first and then decrease along with the increasing of subsections of multi-stage blasting. There must be an optimal mode of multi-stage to improve the permeability of rock reservoir. For relatively large in-situ stress condition, a more subsections of multi-stage blasting would produce a smaller damage area and permeability, and 1-stage blasting would superior to multi-stage blasting to improve the reservoir’s permeability.

This paper is a preliminary exploration of multi-stage blasting in uranium ore layer, and the calculation formula of porosity and permeability is based on previous research results. Therefore, the research results of this paper can only conduct a qualitative analysis of blast-enhancing permeability, but can not give quantitative results of infiltration effect. The next step is to establish the relationship between the volumetric strain rate and permeability of uranium layer rock according to the shock failure tests, and verify the reliability of the method according to the field monitoring results.

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**Data availability statement**

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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Appendix

Def Ini_State_Index; Define the initialization function
  pnt = zone_head
  loop while pnt # null
    if z_group(pnt) = 'reservoir' then
      z_extra(pnt,1) = -(z_sig1(pnt)+z_sig3(pnt)) * (-z_sig1(pnt)+z_sig3(pnt));
    Calculate the initial stress state index (SSI) and store it in extra parameter array index 1 for
    zone pnt.
      z_extra(pnt,3) = 1.0; The value in extra parameter array index 3 for zone pnt is
    initially set to 1.0.
    endif
    pnt = z_next(pnt)
  end_loop
@Ini_State_Index; Execute the initialization function

Def Modify_parameters; Define the function for modifying the parameters involved in
Generalized Hoek-Brown criterion
  Whilestepping; The parameters are updated at each calculation step
  pnt = zone_head
  loop while pnt # null
    if z_group(pnt) = 'reservoir' then
      lamda = -(z_sig1(pnt)+z_sig3(pnt)) * (-z_sig1(pnt)+z_sig3(pnt));
    Calculate the current stress state index.
      z_extra(pnt,2) = 1-exp(-abs((lamda-z_extra(pnt,1))/z_extra(pnt,1))); Calculate
    the stress disturbance index D and store it in extra parameter array index 2 for zone pnt.
    if z_state(pnt,1) # 0 then
      Calculate the rock integrity index
      wzxIndex = 1- abs(z_wptot(pnt))/(abs(z_wptot(pnt))+abs(z_wetot(pnt)))
      if wzxIndex < z_extra(pnt,3) then
        z_extra(pnt,3) = wzxIndex; Update the rock integrity index and store it in
      extra parameter array index 3 for zone pnt.
      endif
    endif
      z_extra(pnt,4) = 100.0 * z_extra(pnt,3); Modify the GSI, and the initial GSI
    is 100.0.
      M_GSI = z_extra(pnt,4)
      M_DDD = z_extra(pnt,2)
      z_prop(pnt,'mb') = 18.0*exp((M_GSI-100)/(28-14*M_DDD)); Modify the mb.
      z_prop(pnt,'a') = 0.5+(exp(-M_GSI/15.0)-exp(-20/3.0))/6.0; Modify the a.
      z_prop(pnt,'s') = exp((M_GSI-100)/(9-3*M_DDD)); Modify the s.
    endif
    pnt = z_next(pnt)
  end_loop
@Modify_parameters; Execute the modifying function