Anisotropic rock permeability evolution model based on wing crack propagation after dynamic load testing

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Abstract. The permeability evolution of rock is essential in geotechnical engineering, which is related to seepage. A permeability evolution model, which is based on the wing crack propagation model and Darcy’s law, is created for rock after dynamic load testing with confining pressures. It is assumed that permeability has two types: isotropic initial permeability and anisotropic microcrack-induced permeability. In this model, the wing crack length is associated with the absorption energy per unit volume of the rock specimen under dynamic loads, in accordance with the surface energy theory. Assuming that the initial crack families are evenly distributed, the contribution of each crack family to permeability in different directions is investigated. In this study, an expression of permeability, which is related to axial stress, confining pressure, and absorbed energy per unit volume, is obtained. Two groups of dynamic load testing with confining pressures of sandstone are conducted using a modified split Hopkinson pressure bar technique. In group A, the incident energy is a variable, whereas in group B, the confining pressure is a variable. After the dynamic load testing, the permeability of the sandstone specimens is measured using the pulse decay method on MTS 815. Owing to the limitations on the test equipment, only the permeability in the direction of the dynamic load is measured. The permeability obtained from the dynamic load testing is in good agreement with the permeability calculated by the model. In this model, the anisotropy of rock permeability is theoretically studied. The minimum microcrack-induced permeability in all directions is about 0.65 of the maximum permeability value. In summary, the model discussed here enables the prediction of the permeability of the rocks under dynamic impact and establishes the relationship between macro-mechanical parameters and micro-mechanical parameters. In addition, it provides a new idea for the research on the anisotropy of rock permeability.

List of Symbols

\( a \) \quad \text{Half length of the initial crack} \\
\( e \) \quad \text{Aperture of crack} \\
\( E_{\text{surf}} \) \quad \text{Energy absorption per unit volume} \\
\( E_{\text{surf}} \) \quad \text{Surface energy used to generate new cracks} \\
\( k_0 \) \quad \text{Isotropic permeability of rock matrix} \\
\( k_c \) \quad \text{Anisotropic permeability by crack propagation} \\
\( \nu \) \quad \text{Fluid flow velocity} \\
\( \nu_0 \) \quad \text{Component of } \nu \text{ in rock matrix} \\
\( \nu_c \) \quad \text{Component of } \nu \text{ in cracks} \\
\( \sigma_{\text{max}} \) \quad \text{Peak dynamic stress} \\
\( \sigma_1 \) \quad \text{Maximum principal stress} \\
\( \sigma_3 \) \quad \text{Minimum principal stress}
fter blasting, the permeability of some rocks increased by the pulse peak pressure or the number of explosions. It was found that the permeability of sandstone ore bodies is very low, which results in low mining efficiency. In China, it is reported that more than 70% of sandstone-type uranium deposits with extremely low permeability are found in a sandstone reservoir [1]. Therefore, the use of dynamic disturbance, such as blasting, is proposed on ore bodies to enhance the permeability to improve mining efficiency [2]. Tunneling in a groundwater-rich area often requires waterproofing considerations [3]. Drilling and blasting are often used for rock tunnel excavation. This means that the impact of blasting on rock permeability should be evaluated. A core issue can be found from the examples above, that is, the effect of dynamic loads on rock permeability.

The existing studies on the evolution of rock permeability under dynamic loads can be divided into two groups. One is about experiment, whereas the other is about numerical simulation and theory. Chen et al. [4] used a pulsed arc electrohydraulic discharge system to generate steam explosion in water to apply a dynamic load to a cement mortar sample also in water. Moreover, they studied the permeability evolution of the cement mortar sample. It was found that the permeability increased as the pulse peak pressure or the number of explosions increased, with the maximum permeability increase of about two orders of magnitude. Wang et al. [2] conducted model tests of blasting-induced permeability enhancement of sandstone-type uranium deposits with low permeability. It was found that the model permeability increased by two to three orders of magnitude after blasting, the permeability-enhanced range was about 70 times the borehole radius, and the suitable uncoupling coefficient range was 1.5–3.0. Yang et al. [5] conducted a one-dimensional coupled dynamic and static load testing on granite and found that the permeability of the granite after the impact increased as the axial pressure increased. Yan et al. [6] used the split Hopkinson pressure bar (SHPB) technique to conduct cyclic impact tests using fixed speed or changing speed on weakly weathered granite. Their results indicate that the permeability of the weathered granite increases after the impact test, but the change pattern is not obvious.

Perol and Bhatb [7] developed a permeability evolution model for brittle materials based on micromechanics at high strain rates (≥100 s⁻¹). Yuan et al. [1] used a two-dimensional Particle Flow Code Program (PFC²D) and the Universal Distinct Element Code Program to conduct blasting simulations on sandstone ore bodies with low permeability. It was found that the permeability of the sandstone increased first and then decreased with the increase in uncoupling coefficient. Wang et al. [8] created a dynamic constitutive model considering rock coupled damage–permeability effect under explosion conditions and applied it to ABAQUS software for the analysis of rock permeability change. It was found that the ore body permeability that is within 80 times the blast hole radius can be increased by two orders of magnitude under a suitable charge uncoupling coefficient.

Existing studies have few considerations on confining pressure and anisotropy. This study presents a method for estimating rock permeability after dynamic load with confining pressure. The SPHB
technique was used to conduct coupled dynamic and static load testing on the sandstone specimens. The permeability of the sandstone specimen was measured, and the effectiveness of the model was verified by comparing the permeability obtained by the test with that calculated by the model.

2. Permeability evolution model

2.1. Assumptions
To simplify the problem, it is assumed that in the initial state, the permeability of the rock is isotropic, with a value of $k_0$. Under dynamic load, the permeability change is anisotropic, with a value of $k_m$, where $m$ denotes the direction. Initial cracks occur inside the rock, assuming a uniform distribution of the initial cracks. Suppose that under dynamic load, some initial cracks expand to form wing cracks, as presented in Fig. 1, which are assumed to cause permeability changes in different directions. The creation of an anisotropic permeability evolution model is expected, which is based on wing crack propagation theory, Darcy’s law, and cubic law.

![Figure 1. Crack propagation of brittle materials under compressive stress](image)

2.2. Formulation

2.2.1. Angle range of propagated cracks. In the case of a single crack, the crack is affected by the maximum principal stress $\sigma_1$ and the minimum principal stress $\sigma_3$, and both are compressive. The lateral stress coefficient is introduced to represent the ratio of $\sigma_3$ and $\sigma_1$:

$$\lambda = \frac{\sigma_3}{\sigma_1}$$

In the below equation, $\psi$ denotes the angle between the crack and $\sigma_1$, as presented in Figure 1. According to the study by Ashby and Hallam [9], the mode I stress intensity of the tip of the crack can be expressed as follows:

$$K_1 = \sigma_1 \sqrt{\frac{\pi a}{\sqrt{3}}} \left[ (1 - \lambda) (\sin 2\psi + \mu \cos 2\psi) - \mu (1 + \lambda) \right]$$

where $a$ denotes the half length of the crack and $\mu$ the friction coefficient.

The angles of the cracks inside the rock are different. Under loads, only the crack whose angle satisfies the cracking initial conditions can propagate.

Considering the cracking initial condition:

$$K_i \geq K_{IC}$$

(3)
The angle range of the propagated cracks can be expressed as follows:

\[
\frac{\sin^{-1} A - \tan^{-1} \mu}{2} \leq \psi \leq \frac{\pi}{2} - \frac{\sin^{-1} A + \tan^{-1} \mu}{2}
\]

\[
A = \frac{\sqrt{3} K_{IC} + \mu(1 + \lambda)}{\sigma_0 \sqrt{\pi a}} = \frac{\sqrt{1 + \mu^2 (1 - \lambda)}}{\sqrt{1 + \mu^2 (1 - \lambda)}}
\]

(4)

where \(0 < \psi < \pi/2\).

2.2.2. Estimation of wing crack geometric parameters. To simplify the problem, this study adopts the same assumption as Ashby and Sammis [10] and believes that the wing crack is disc-shaped and parallel to the direction of the maximum principal compressive stress. The crack length is denoted by \(l\), as presented in Figure 2.

According to fracture mechanics, the new surface formed by crack propagation needs to consume surface energy. Suppose the surface energy required to create a crack with radius \(r\) is

\[
E_{surf} = 2\pi r^2 \Gamma
\]

where \(\Gamma\) denotes the surface energy consumed per unit area.

In dynamic load testing, the surface energy consumed by the new cracks is derived from the energy absorbed by the rock specimen. It can be inferred that under other unchanged conditions, the more energy the sample absorbs in the dynamic loads, the more surface energy it can use to create new cracks. Simply, it is assumed that the surface energy used to create new cracks is proportional to the energy absorption per unit volume \(E_v\) of the rock sample as

\[
E_{surf} \propto E_v
\]

(5)

Applying it to the wing crack model gives

\[
l^2 \propto E_v
\]

(6)

From Equation (4), it is known that under loads, only cracks with an angle within a certain range propagate. Therefore, it is reasonable to introduce a function related to \(\psi\) as the term of \(l\). Simply, it is assumed that the length of the wing crack is positively correlated with \(f(\psi)\).

\[
l \propto f(\psi)
\]

(7)

Noting a part of Equation (2) \( (1 - \lambda)(\sin 2\psi + \mu \cos 2\psi) - \mu(1 + \lambda) \), it controls the sign of \(K_{Ic}\).
Therefore, it is able to establish the connection between $\psi$ and $l$. Let it be $f(\psi)$:
\[
f(\psi) = (1-\lambda)(\sin 2\psi + \mu \cos 2\psi) - \mu (1+\lambda)
\]
(9)
From the above equations, $l$ can be estimated by introducing a coefficient $\eta_1$:
\[
l = \eta_1 \sqrt{E_v} \left[(1-\lambda)(\sin 2\psi + \mu \cos 2\psi) - \mu (1+\lambda)\right]
\]
(10)
According to the geometric relationship, the aperture of crack $e$ is assumed to be proportional to $l$ by introducing a dimensionless coefficient $\eta_2$:
\[
e = \eta_2 l
\]
(11)
It has been discussed that an original crack propagates under loads, and then a pair of wing cracks are created. Due to the complication of calculating the flow of three connected cracks, the equivalent crack is introduced to represent the three cracks. The angle between the equivalent crack and $\sigma_1$ is the equivalent angle $\psi'$, as presented in Figure 3.

\[\text{Figure 3. Equivalent angle}\]
\[\text{Figure 4. Crack surface in the Cartesian coordinate system}\]

According to the geometric relationship, there is
\[
l = \frac{a}{\sin(\psi - \psi')} = \frac{a}{\sin(\psi)}
\]
(12)

2.2.3. Crack distribution. In the Cartesian coordinate system, let the normal vector of one crack surface be $n$, as presented in Figure 4. The angle between $n$ and $z$ is $\phi$, and the angle between the projection of $n$ on the $xy$ plane and $x$ is $\theta$. It should be noted that $\phi$ is different from $\psi$. The relationship between them is expressed as
\[
\psi = \frac{\pi}{2} - \phi
\]
(13)
In representative elementary volume (REV), a group of cracks with parallel $n$ is referred to as a crack family. Assuming that the REV is $\Omega$, the number of original cracks in REV is $N_v$. It is assumed that, in the original state, the $n$ of all crack families is evenly distributed. It gives
\[
E(\phi, \theta) = c
\]
(14)
where $E(\phi, \theta)$ denotes the probability density in REV and $c$ an undetermined constant. Considering the property that the sum of probability densities is 1
\[
\int_0^{2\pi} \int_0^\pi E(\phi, \theta) \sin \phi d\phi d\theta = 1
\]
(15)
c is obtained.
2.2.4. Contribution of cracks to permeability in different directions. The direction of the crack influences the fluid flow in it. Considering a pressure gradient $\Delta p$ in the direction $\mathbf{m}(\phi_m, \theta_m)$ and a crack with a normal vector $\mathbf{n}(\phi, \theta)$, let the angle between the crack face and $\mathbf{m}$ be $\psi_m$. If the velocity of the fluid flow of the crack is $\mathbf{v}$, the flow velocity projection in direction $\mathbf{m}$ is $v\cos(\psi_m)$, which is the contribution of the crack to direction $\mathbf{m}$. From Equation (13), it is easy to obtain

$$ \cos(\psi_m) = \sqrt{1 - \cos^2 \langle n, m \rangle^2} $$

(17)

where

$$ \cos(\langle n, m \rangle) = \frac{n \cdot m}{|n||m|} = \sin \phi \cos \theta \sin \phi_m \cos \theta_m + \sin \phi \sin \theta \cos \phi_m \sin \phi_m + \cos \phi \cos \phi_m $$

(18)

Especially, limiting $\mathbf{m}$ to the $xz$ plane makes $\theta_m = 0$ and gives

$$ \cos(\langle n, m_{xz} \rangle) = \sin \phi \cos \theta \sin \phi_m + \cos \phi \cos \phi_m $$

(19)

Letting $\mathbf{m}$ be parallel to $z$ makes $\phi_m = 0$ and gives

$$ \cos(\langle n, z \rangle) = \cos \phi $$

(20)

2.2.5. Expression of permeability. Based on the previous discussion, the permeability expression is accessible. In this study, the permeability calculation refers to the assumption of Hu et al. [11] that rock permeability is composed of the isotropic permeability of rock matrix ($k_0$) and the anisotropic permeability caused by crack propagation ($k_c$):

$$ k = k_0 + k_c $$

(21)

According to Darcy’s law, there is

$$ v = \frac{k}{\mu_v} \nabla p = \frac{k_0}{\mu_v} \nabla p + \frac{k_c}{\mu_v} \nabla p = v_0 + v_c $$

(22)

where $v$ denotes the fluid flow velocity, and $v_0$ and $v_c$ denote the components of $v$ in rock matrix and cracks. $\Delta p$ denotes the pressure gradient and $\mu_v$ the fluid viscosity.

Considering the cubic law in a crack, there is

$$ v_c = \frac{e^2}{12\mu_v} \nabla p $$

(23)

Considering the equivalent crack, its contribution to the permeability of direction $\mathbf{m}$ is

$$ v_{c,m} = \frac{e^2}{12\mu_v} \nabla p \cdot \cos(\psi_m) $$

(24)

In REV, averaging of the flow velocity of the crack gives

$$ \overline{v}_{c,m} = \frac{1}{\Omega} \int_{\Omega} \frac{e^2}{12\mu_v} \nabla p \cdot \cos(\psi_m) \, d\Omega $$

(25)

The volume of the wing crack can simply be

$$ \Omega_{c,m} = e \cdot \pi t^2 $$

(26)

In REV, the flow velocity of volume without crack is zero, and the integration can be performed only on the crack volume, which gives

$$ \overline{v}_{c,m} = \frac{1}{\Omega} \int_{\Omega} \frac{e^2}{12\mu_v} \nabla p \cdot \cos(\psi_m) \cdot e \pi t^2 \cdot \frac{N_v}{4\pi} \, dS $$

(27)
then,

$$\bar{v}_{c,m} = \frac{1}{4} \frac{N_v}{\Omega} \frac{\nabla p}{2 \mu_v} \int_0^{2\pi} \int_0^\pi e^3 \sin \psi_m \cos \phi \, d\theta \, d\psi$$

Considering the symmetry and a fact that $\phi$ needs to be within a certain range to make $l$ greater than zero,

$$\bar{v}_{c,m} = \frac{1}{4} \frac{N_v}{\Omega} \frac{\nabla p}{2 \mu_v} \int_0^{2\pi} \int_{\phi_{\text{min}}}^{\phi_{\text{max}}} e^3 \sin \psi_m \cos \phi \, d\theta \, d\psi$$

where $\phi_{\text{min}}$ and $\phi_{\text{max}}$ denote the minimum and maximum values of $\phi$ that can satisfy the initiation conditions in the range of 0 to $\pi/2$. They can be obtained using equations (4) and (13). Comparing Equation (22), the permeability in the direction $m$ can be obtained:

$$k_m = k_0 + \frac{1}{2} \frac{N_v}{\Omega} \int_0^{2\pi} \int_{\phi_{\text{min}}}^{\phi_{\text{max}}} e^3 \sin \psi_m \cos \phi \, d\theta \, d\psi$$

### 3. Dynamic load testing for the validation of the model

#### 3.1. Dynamic load testing

Two groups of dynamic load testing were conducted on sandstones to investigate the permeability evolution. The sandstones were processed into cylindrical specimens with a diameter of 50 mm and a length of 50 mm, as presented in Figure 5.

![Figure 5. Sandstone specimens](image)

In addition, two standard cylindrical specimens, having a diameter of 50 mm and a length of 100 mm, were processed for the uniaxial compression test. The results revealed that the uniaxial compressive strength, Young’s modulus, and Poisson’s ratio of the specimens were 36.53 MPa, 10.99 GPa, and 0.198, respectively.

| Specimen No. | Length (mm) | Diameter (mm) | Confining pressure (MPa) | Gas pressure (MPa) |
|--------------|-------------|---------------|--------------------------|-------------------|
| W            | 50.17       | 48.88         | 5, 10, 15, 20, 25        | /                 |
| A1           | 50.13       | 49.93         | 5                        | 0.4               |
| A2           | 50.13       | 49.93         | 5                        | 0.6               |
| A3           | 50.13       | 49.93         | 5                        | 0.8               |
| A4           | 50.13       | 49.93         | 5                        | 0.9               |
| A5           | 50.09       | 49.14         | 5                        | 1.0               |
| A6           | 50.09       | 49.14         | 5                        | 1.2               |
| B1           | 50.09       | 49.14         | 5                        | 1.0               |
| B2           | 50.13       | 48.94         | 10                       | 1.0               |
The SHPB technique was used to conduct the tests, and its details can be found in the research by Li et al. [12]. The scheme of the dynamic load testing is presented in Table 1. Two groups of dynamic load testing with confining pressures of sandstone were conducted. The group A specimens were impacted with different pressures in the fuel tank to change the incident energy, whereas the group B specimens were impacted with different confining pressures. For comparison, specimen W was tested to measure its permeability without impact. Information related to the permeability evolution model in the dynamic load testing is presented in Table 2.

**Table 2. Results of the dynamic load testing**

| Specimen No. | $\sigma_{\text{max}}$ (MPa)$^a$ | $E_v$ (J·cm$^{-3}$) |
|--------------|-------------------------------|---------------------|
| A1           | 63.76                         | 0.10                |
| A2           | 106.88                        | 0.33                |
| A3           | 117.81                        | 1.02                |
| A4           | 117.55                        | 0.55                |
| A5           | 115.16                        | 0.68                |
| A6           | 126.57                        | 1.39                |
| B1           | 115.16                        | 0.68                |
| B2           | 151.97                        | 0.77                |
| B3           | 160.44                        | 0.74                |
| B4           | 160.20                        | 0.84                |
| B5           | 178.43                        | 0.62                |

$^a$ $\sigma_{\text{max}}$ denotes the peak dynamic stress of the specimen under dynamic loads.

**3.2. Permeability test**

After the dynamic load testing, the permeability of all specimens was measured using the pulse decay method on the MTS 815 electrohydraulic servo-controlled rock mechanics testing system. The confining pressure of each specimen in the measurement was the same as that in the dynamic load testing. The specific test method is described by Wang et al. [13]. The test results are presented in Table 3.

**Table 3. Permeability of the specimens**

| Specimen No. | Confining pressure (MPa) | Permeability by experiment ($m^2$) | Permeability by model ($m^2$) |
|--------------|--------------------------|-----------------------------------|-------------------------------|
| W            | 5                        | $3.16 \times 10^{-18}$            | /                             |
| W            | 10                       | $2.04 \times 10^{-18}$            | /                             |
| W            | 15                       | $1.98 \times 10^{-18}$            | /                             |
| W            | 20                       | $1.93 \times 10^{-18}$            | /                             |
| W            | 25                       | $1.61 \times 10^{-18}$            | /                             |
| A1           | 5                        | $5.22 \times 10^{-18}$            | $3.23 \times 10^{-18}$        |
| A2           | 5                        | $6.85 \times 10^{-18}$            | $5.48 \times 10^{-18}$        |
| A3           | 5                        | $3.09 \times 10^{-17}$            | $4.54 \times 10^{-17}$        |
| A4           | 5                        | $2.29 \times 10^{-17}$            | $1.21 \times 10^{-17}$        |
| A5           | 5                        | $2.54 \times 10^{-17}$            | $1.82 \times 10^{-17}$        |
| A6           | 5                        | $9.07 \times 10^{-17}$            | $9.95 \times 10^{-17}$        |
| B1           | 5                        | $2.54 \times 10^{-17}$            | $1.82 \times 10^{-17}$        |
Before calculating the permeability, it is important to determine the values of several parameters. However, due to the limitations on the experimental conditions, the values of these parameters cannot be directly obtained. For the original crack length $a$, it is not a constant. The original crack originates from the internal defects in the rock formation and evolution, and a large part of this defect is the boundary between the crystal particles and the crystal particles. In this study, the statistical values of Ashby and Sammis [10] are used, in which $a = 1.0$ mm. The friction coefficient $\mu$ is roughly between 0.55 and 0.64 for rock materials. Its value in this study is assumed to be 0.6. In terms of the fracture toughness $K_{\text{IC}}$, studies show that a correlation between the fracture toughness and its uniaxial compressive strength exists [14,15]. According to the study by Bao et al. [15], the sandstone with a strength of around 36.53 MPa has a fracture toughness of about 0.4 MPa$\cdot$m$^{1/2}$, which is used in this study. For the initial crack density $N_c/\Omega$, the statistical values of Ashby and Sammis [10] are used, in which $N_c/\Omega$ is about 0.1 mm$^{-3}$.

When calculating the permeability of group A and B specimens, the initial permeability of the specimens is directly the permeability of specimen W (with the same confining pressure). Using Equation (30), the permeability change by dynamic loads is calculated. $\sigma_i$ denotes the sum of $\sigma_{\text{max}}$ and the confining pressure and $\sigma_1$ the confining pressure. Two parameters, $\eta_1$ and $\eta_2$, are set to 0.027 and 0.01 by trial calculation. Finally, the permeability of the specimens in the direction parallel to $\sigma_i$ is obtained and presented in Table 3.

The comparison of the permeability calculated by experiment and that by theoretical model is presented in Figure 6, from which a good consistency can be observed. In addition, Figure 7 presents the photographic view of the three typical specimens after the impact test. From Fig. 6 (a), it can be seen that when the confining pressure is fixed at 5 MPa, the sandstone permeability basically increases as the gas pressure increases. However, there is a sudden increase in the permeability of the specimen loaded at the gas pressure of 0.8 MPa, which may be caused by the discreteness of the sandstone specimen. It indicates that when the air pressure is lower than 0.6 MPa, fracturing the specimen is not sufficient (Fig. 7(a)). Conversely, an air pressure greater than 0.6 MPa can cause macro fracture of the specimen (Fig. 7(b) and (c)). The macro cracks obliquely propagate along the direction of the principal stress, which results in the obvious increase of permeability. Conversely, when the gas pressure is fixed at 1.0 MPa, the sandstone permeability decreases as the confining pressure increase (Fig. 6(b)). The above results indicate that with the increase in depth, the influence of the dynamic disturbance on rock fracturing and permeability improvement effect of the rock gradually weakens, but as long as the incident energy exceeds the critical value, the permeability of the rock will be effectively improved.

### Table 3

| Group | Initial Permeability | Increase in Permeability |
|-------|----------------------|--------------------------|
| B2    | 10                   | 1.31×10$^{-17}$          |
| B3    | 15                   | 6.14×10$^{-18}$          |
| B4    | 20                   | 6.46×10$^{-18}$          |
| B5    | 25                   | 4.71×10$^{-18}$          |

**3.3. Permeability obtained by the model**
Figure 6. Comparison of permeability calculated by experiment and by the theoretical model; (a) group A and (b) group B

Figure 7. Photographic view of the specimens after the impact test; (a) specimen A2, (b) specimen A3, and (c) specimen A6

3.4. Anisotropy of the permeability

In the previous subsection, the permeability of the specimens in the direction of $\sigma_1$ (parallel to $z$) is calculated for comparison with the permeability obtained by experiment. Due to the limitations on the experimental conditions, only the permeability in one direction can be measured. In fact, the permeability of the specimens in any direction can be obtained by the model. Figure 8 presents the permeability of specimen A4 in the $xz$ plane in any direction ($\varphi_0$, 0). From the figure, it can be seen that the permeability $k_c$ (caused by crack propagation) decreases as $\varphi_0$ increases in the range of $0^\circ$–$90^\circ$. While $\varphi_0 = 0$, $k_c$ takes the maximum value, which corresponds to the direction of $\sigma_1$. While $\varphi_0 = 90^\circ$, $k_c$ takes the minimum value, which corresponds to the direction of $\sigma_3$. $k_0$ denotes the initial permeability and is isotropic. The total permeability $k$ is the sum of $k_0$ and $k_c$. Its anisotropy depends on the proportion of $k_0$ and $k_c$. The ratio of $k$ (or $k_c$) at $\varphi_0 = 0^\circ$ and $\varphi_0 = 90^\circ$ of the specimens is presented in Table 4. From Table 4, it is can be clearly seen that the anisotropy of $k$ is various. However, the anisotropy of $k_c$ is not much different, with a ratio of around 0.65. Maleki and Pouya [16] used numerical simulation to study the anisotropy of brittle rock permeability. They found that for compressive loads, the minimum permeability is about 0.5 of the maximum permeability in different directions. For tensile loads, the minimum permeability is about 0.4.
4. Conclusion

Based on the wing crack propagation model and Darcy’s law, a rock permeability evolution model is created for dynamic loads with confining pressure. Assumptions have been made to build the base of the model. The initial permeability $k_0$ of the rock is isotropic. Under dynamic loads, wing cracks propagate from the initial cracks, which results in the anisotropic change of permeability. With the assumptions, the permeability expression in any direction is obtained, and this expression is related to the axial stress, confining pressure, and absorption energy per unit volume of the rock specimens.

Two groups of dynamic load testing were conducted on sandstones using the SHPB technique. Group A specimens were tested with different incident energy, whereas group B specimens were tested with different confining pressures. Subsequently, the permeability of all specimens was measured using both the MTS-815 testing system and the established model. It was observed that the experimental
results and analytical results were in good agreement. Moreover, the results indicate that the influence of the dynamic disturbance on rock fracturing and permeability improvement effect gradually weakens as the depth increases, but as long as the incident energy exceeds the critical value, the permeability of the rock will be effectively improved.

Finally, the anisotropy of the permeability in the model is studied. It is found that the maximum value of permeability occurs in the direction of the maximum principal stress, whereas the minimum value occurs in the direction of the minimum principal stress. The minimum value of permeability caused by crack propagation $k_c$ is around 0.65 of the maximum value, and the anisotropy of the overall permeability depends on the proportion of $k_0$ and $k_c$.

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