Quantification analysis of geometric characteristics of micro crack network on fault rock surface

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Abstract
Faults are common water conduits in coal mines, with variable permeability based upon the extent of cracks along the fault plane. In this study, three samples from a fault were obtained from a mining area in Southwest Shandong, China to determine the geometric characteristics, including crack density, fractal dimension, and crack connectivity. For microstructural analysis of fault rock specimens, scanning electron microscopy (SEM), x-ray diffraction (XRD), and plane-polarized light microscopy tests were used, and the geometric characteristics were calculated. A nonuniformity coefficient that considers the mineral composition is proposed to describe the micro-crack network of fault rocks. The results show that there is a significant positive correlation among three geometric characteristic parameters, and the nonuniformity coefficient is positively correlated with those parameters of the crack network. The crack extension forms of the three fault rock samples are different, which is related to the different fracture toughness of the mineral particles. The optical photomicrographs and SEM images show that crack networks are most developed in the samples with the least clay content. There is a negative correlation between clay content and the geometric parameters of the crack network, which may be related to the friction coefficient of clay.

Keywords Fault rock · Crack network · Geometric characteristics · Clay

Introduction
A rock mass in the fault zone breaks due to structural stress. There are often numerous cracks in the rock located along the fault plane. The structural plane on the macro scale determines the permeability of the fault to a great extent (Bauer et al. 2016; Bense and Person 2006; Caine et al. 1996; Cooke et al. 2018). In addition, the fault rock itself has also developed microcracks (Kim et al. 2004). Although these microcracks have little effect on permeability, these defects tend to expand (Liang et al. 2012; Liu et al. 2016), especially during manual excavation in a coal mine (Donnelly 2006). The quantitative analysis of the rock crack network is critical to promoting the mechanical research of natural fissured rock. It is necessary to carry out quantitative statistical analysis on the crack network to obtain the geometric parameters (Saevik and Nixon 2017; Zhong et al. 2017). The selection of geometric parameters is the emphasis of crack network research. Typical parameters studied include crack density, crack spacing, and crack strike, amongst others (Li 2015; Zhou et al. 2011). The connectivity of the crack network is a crucial parameter for estimating the permeability of fault rocks (Saevik and Nixon 2017). There are numerous descriptions of the concept of connectivity, most of which are based on the intersection of cracks (Kushch et al. 2009; Robinson 1983; Zhou et al. 2011). In addition, fractal characteristics can also be used as an index to describe the complexity of a crack network (Jafari and Babadagli 2012; Miao et al. 2015). Topology, which also incorporates the attributes of network nodes, has been widely used in crack network research in recent years and has several advantages (Lahiri 2021; Li et al. 2020; Sanderson and Nixon 2018). New techniques are constantly applied to provide support for the quantitative study of rock crack networks. In addition to conventional acoustic positioning methods, imaging technologies such as...
scanning electron microscopes (SEM) and X-ray CT are also widely used to observe fractures within samples. These techniques can provide two-dimensional or three-dimensional images at microscopic levels (microns) (Litorowicz 2006; Mac et al. 2021).

In recent years, studies on the synthetic and pre-existing crack network of rocks have increased (Li et al. 2020; Liang et al. 2012; Yang et al. 2009). Most of them pay attention to the percolation properties of the crack network and put forward some formulas for approximate calculation of the rock permeability (Hamzehpour et al. 2009; Jafari and Babadagli 2012; Jiao et al. 2018; Saevik and Nixon 2017). Ideal crack geometry characteristics can be obtained from synthetic and pre-existing crack networks, while natural crack networks are generally more complex and unpredictable (Lahiri 2021; Walker et al. 2013; Zhong et al. 2017). During the diagenetic processes of fault rocks, there are complex deformation, cataclasis, compaction, and cementation, which have significant effects on the crack network characteristics (Pei et al. 2015). Clay smearing has a significant influence on the percolation properties of fault rocks (Bense et al. 2013; Eichhubl et al. 2005; Vrolijk et al. 2016). Some original micro-pores will be occupied by fine-grained clay or phyllosilicate minerals (Çiftçi et al. 2013; Pei et al. 2015). Although previous scholars applied a variety of geometric parameters to study crack networks and achieved satisfactory results, the natural crack networks of fault rocks have not been well analyzed in terms of their properties and controlling factors, because the crack network development of fault rock can involve the inhomogeneity of mineral composition, not just geometric parameters. (Leung and Zimmerman 2012; Li 2015; Miao et al. 2015).

This paper integrates the previous studies, and the crack networks of fault rock samples from Shandong, China are quantitatively studied. The emphasis of this research is focused on the effect of clay on the crack network of fault rock. In this paper, a nonuniformity coefficient is proposed to describe the micro-crack network of fault rocks that consider the mineral composition. Besides, we investigate the relationship between clay content and crack extension forms and geometric characteristics.

**Materials and methods**

**Fault samples**

Three samples were collected from a mining area in the southwest of Shandong Province, China (Fig. 1). The overall geological structure in the region is principally composed of 70 faults, with a density of 11/km². Large and medium-sized faults with large offsets and extensive extension dominate the region. To determine the specific conditions of large faults in the mining area, geological exploration holes were drilled to uncover the fault zone at a depth of 673.73–739.12 m. A normal fault with an offset of 120–140 m is located in the upper part of the Shanxi Formation. The fault extends for 65.39 m. 51.30 m of core length was recovered from the borehole, with a 78.45% core recovery rate. The lithology of the core is mainly sandy mudstone, medium sandstone, and...
siltstone. The color is mainly grayish-black to grayish-white. Locally, it contains plant debris fossils and calcite veins. The core at a depth of 689.12–701.32 m (mainly medium-grained sandstone, including a small amount of siltstone and mudstone) is relatively complete. The core at a depth of 701.32–712.74 m is mudstone containing clastic plant fossils and a large amount of argillaceous material, with an increase towards the coal seams. Below the coal seam is siltstone with cracks. The rock is initially fractured along the fault plane in the core, followed by an intact section, and then fractured once again in the latter section. In addition, there are significant differences in the degree of fragmentation and weathering in different layers. The core is divided into upper, middle, and lower sections according to the sample characteristics and depth.

**Test methods and geometric characteristic parameters**

This study observed the crack morphology of samples taken from a fault plane by plane-polarized light and scanning electron microscopy (SEM). Under certain pressure and temperature conditions, blue epoxy resin was pressed into the rock. It was allowed to fully cure, and the thin sections were polished. The thin sections were placed under the plane-polarized light microscope for observation, and high-resolution images were taken. The microstructures of the fault rocks were observed by scanning electron microscopy. The phase composition was determined by XRD. The diffraction results were analyzed using the standard comparison card in Jade analysis software to conduct semi-quantitative mineral analysis (Nikkah et al. 2017).

The optical photomicrographs were imported into AutoCAD software to analyze the geometric characteristics of the cracks in fault rocks. The cracks that can be distinguished and recognized were identified using polylines, and a digital generalized crack network was obtained for geometric characteristics analysis. The crack characteristics were divided into single cracks and crack networks. Single cracks had their length, opening, and roughness measured. Crack networks are characterized by their geometric characteristic parameters, including crack density, connectivity, fractal characteristics of the crack network, and so on.

**Crack density**

There are different definitions of crack density. When studying cracks in concrete structures, Litorowicz (2006) defined crack density as the ratio of the total length of cracks in each image to the image area. Leung and Zimmerman (2012) defined crack density as the total number of cracks per unit area when estimating the hydraulic conductivity by statistical parameters of random crack networks. In the effective medium theory, cracks are usually considered inclusions in porous materials. The crack density is usually expressed as a dimensionless area density (Bristow 1960). In this paper, the crack density is calculated by this dimensionless method.

\[
\rho = \frac{1}{A} \left( \sum_{i=1}^{n} \frac{l_i}{2} \right)^2
\]

where \(A\) is the area of the digitized image, which is 10.63 mm\(^2\), \(n\) is the total number of cracks in the image area, and \(l_i\) is the length of the crack.

**Fractal dimension**

The fractal dimension describes the crack distribution. The primary method to calculate the fractal dimension is the grid covering method. Natural cracks in rocks have a certain self-similarity (Mandelbrot 1982). \(F\) is a set of bounded points on a plane that are contained in a rectangular region. The rectangular region is divided into a smaller grid whose side length is \(\varepsilon\) determined by a certain proportion \(r\). If the number of the non-null grid is \(N(r)\), the capacity dimension \(D_c\) is defined as:

\[
D_c = -\lim_{r \to 0} \frac{\ln N(r)}{\ln r}
\]

**Crack connectivity**

The topological property of a crack network indicates that each crack’s connection structure will not change due to a change in crack length and node position. This research method for crack connectivity can avoid the influence of the scale effect because topology considers the inherent properties of the crack network (Valentini et al. 2007).

Any crack network is made up of nodes and segments, according to topological graph theory. Nodes are the points...
where two cracks intersect or pinch out, and segments connect two nodes. As shown in Fig. 2, nodes can be divided into X-type nodes (cross), Y-type nodes (adjacent), and I-type nodes (isolated) (Sanderson and Nixon 2018). The connectivity \( f \) of a crack network can be calculated from the number of nodes of the above three types.

Saevik and Nixon (2017) compared five topological graphs used to describe the connectivity of a crack network and obtained the expression of connectivity after fitting the most suitable parameter for predicting the hydraulic connectivity of variable topological crack mode:

\[
\begin{align*}
\eta &= \frac{4n_x + 2n_y}{4n_x + 2n_y + \rho} \\
\rho &= \max(0, 2.94\eta - 2.13) \\
\end{align*}
\]  

where \( \eta \) is the equivalent average connection number of each crack, \( f \) is the connectivity of the crack network, \( n_x, n_y \) and \( n_I \) are the number of X-type nodes, Y-type nodes, and I-type nodes, respectively.

Table 1 Geometric parameters of the crack networks for the three samples

| Depth             | \( n_x \) | \( n_y \) | \( n_I \) | \( \eta \) | \( \rho \) | \( D_c \) |
|-------------------|-----------|-----------|-----------|------------|-----------|----------|
| 681.1 m–681.7 m   | 0         | 7         | 26        | 1.03       | 0.47      | 0.48–1.29|
| 701.6 m–702.8 m   | 14        | 143       | 50        | 2.57       | 1.25      | 0.90–1.52|
| 735.7 m–737.3 m   | 0         | 1         | 13        | 0.39       | 0.44      | 0.40–1.14|

Fig. 3 Optical photomicrographs taken under plane-polarized light (PPL) of the three samples from the fault rock, the binary images obtained by the CAD and statistical diagram of crack length: a Sample depth 681.1–681.7 m, b Sample depth 701.6–702.8 m, c Sample depth 735.7–737.3 m
Nonuniformity coefficient

Ke et al. (2011) established a virtual internal bond model based on mesodamage and simulated the dynamic process of crack generation and propagation in anisotropic rocks. The results show that a higher uniformity coefficient corresponds to higher macromechanical strength. Xia et al. (2021) defined the quantitative calculation method of the nonuniformity coefficient based on a normal distribution, which is the ratio of the standard deviation of Young’s modulus to expectation. The concept of nonuniformity coefficient is also applicable here because the fault rock also has a nonuniform strength distribution and a random mineral distribution. However, the proportion of main minerals in a rock mass also dramatically impacts the rock properties. Based on the research of Xia et al. (2021), Eq. 4, which takes into account the effect of mineral content, is proposed to describe the nonuniformity coefficient:

![Fractal dimensions and average values of the crack networks for the three samples](Fig. 4)

![SEM images of the three samples at different magnifications](Fig. 5)

| (a) 681.1m–681.7m | (b) 701.6m–702.8m | (c) 735.7m–737.3m |
|------------------|------------------|------------------|
| ![Image](a) | ![Image](b) | ![Image](c) |
| ![Image](Micro pore) | ![Image](Fine particle) | ![Image](Coarse particle) |
| ![Image](Coarse particle) | ![Image](Micro pore) | ![Image](Coarse particle) |
| ![Image](Coarse particle) | ![Image](Micro pore) | ![Image](Coarse particle) |
where \( c \) is the nonuniformity coefficient; \( E_i \) is the Young’s modulus of a mineral, GPa; \( \omega_i \) is the content of the mineral in a rock mass.

**Results**

The rock samples from the fault plane contain primarily quartz, with additional kaolinite and organic matter (Fig. 3). The quartz particles in the upper sample are generally small, and there are locally large ones (Fig. 3a). The pores between quartz grains are occupied by enriched kaolinite. Cracks are found throughout the sample, and have similar strikes. The sample from the middle section contains low amounts of clay minerals (Fig. 3b). Some cracks within this sample are filled with calcite and have a high degree of fragmentation. The maximum width of the cracks is about 0.06 mm. The lower section sample consists mostly of kaolinite, with minor amounts of quartz (Fig. 3c). Because it is close to the coal seam, there is increased black organic matter throughout the sample (Fig. 3c).

The crack statistics on the surface of the fault rock samples are shown in Fig. 3. There are 19 cracks on the fault sample on the surface selected at a depth of 681.1–681.7 m. The crack lengths range from 0.08 to 2.60 mm, and the cracks with a length of less than 0.5 mm account for 36.84% of the total number of cracks (Fig. 3a). The crack network on the surface of the fault sample at a depth of 701.6–702.8 m is well developed, with a total of 121 cracks (Fig. 3b). The crack lengths range from 0.06 to 2.73 mm. Cracks with lengths of less than 0.5 mm account for 67.77% of the total, and cracks with lengths greater than 1 mm account for 9.92%. There are only seven cracks on the surface of the sample at a depth of 735.7–737.3 m, of which one crack is 4.27 mm long. The other cracks are less than 1 mm. Generally, this sample is dominated by short and small cracks.

The calculated geometric parameters of the crack network are shown in Table 1. The crack density of the middle section is 1.25, about three times that of the other two sections. The fractal results of the three samples show that the average value of the fractal dimension of the cracks in the middle section is 1.27, the highest of the three samples. The crack development degree of the fault sample in the middle section is the highest, followed by the upper sample, and the lower sample is the lowest (Fig. 4).

According to the results of SEM (Fig. 5), numerous cracks and micropores are on the surface of the sample. The crack length can reach hundreds of microns, some cracks have been connected, and mineral particles can be seen in the cracks. There are many striae and a long crack on the surface of the upper sample; the crack structural planes on both sides are uneven, and some cracks contain fine or coarse mineral particles. In the middle sample, there are...
large black patches and small white mineral particles. In addition, there are three connected cracks, which result in more microcracks. At 5000 times magnification, the crack structure is observed to be complex, and the crack surface is rough. Only one crack is developed on the selected surface of the lower section of the sample. Most other cracks are closed on this sample, and the width of some cracks is about 5 μm.

The results of the XRD indicate that all three samples contain quartz and kaolinite. The middle section sample also has muscovite, microcline, and albite. The kaolinite content of the lower sample is the highest (Fig. 6). The Young’s modulus of specific minerals were not tested in this study. The Young’s modulus of quartz, kaolinite, muscovite, microcline, and albite tested in other studies is used here to calculate the nonuniformity coefficient (Benazzouz and Zaoui 2012; Luu et al. 2021; Zhang et al. 2009). The Young’s modulus values used in this study are 105.6 GPa (quartz), 40.7 GPa (kaolinite), 74.4 GPa (muscovite), 73.6 GPa (microcline), and 86.0 GPa (albite). The nonuniformity coefficient calculated is shown in Table 2.

| Depth (m)     | Mineral content | Nonuniformity coefficient |
|---------------|-----------------|---------------------------|
|               | Quartz (%)      | Kaolinite (%)             | Muscovite (%) | Microcline (%) | Albite (%) |               |
| 681.1–681.7   | 85.9            | 14.1                      | –             | –             | –          | 1.76          |
| 701.6–702.8   | 40.8            | 7.5                       | 28.5          | 14.3          | 8.8        | 2.34          |
| 735.7–737.3   | 38              | 62                        | –             | –             | –          | 0.47          |

**Discussion**

**Correlation of geometric parameters of crack network**

The differences in crack formation of the three fault rock samples are shown by optical photomicrographs and SEM images. Due to the strength difference between quartz and clay, stress concentrations easily form in the cementation area under a load, and microcracks are more likely to appear. When the crack contacts mineral particles at a nearly parallel angle, the path of least resistance (least energy required) is preferentially selected, called surrounding extension (Fig. 5a). The mineral particles also change the direction of the extension and form branching extensions (Fig. 3a). The cracks may also break through mineral particles if the strength is weak, called fracture extension (Fig. 3c) (Zhang et al. 2021). The crack density, connectivity, and fractal dimension as quantitative indicators to describe the development degree of the crack network. These three parameters all have the maximum value in the middle sample, followed by the upper sample, and the lowest value in the lower sample. The calculation of crack density is based on the crack length. Connectivity is based on the topological properties of the network. The type and number of crack intersections are involved. Fractal Dimension studies the self-similarities of crack networks. The evaluation results of these three indicators are similar and have consistency (Fig. 7).

There is an apparent positive correlation between the nonuniformity coefficient and the geometric characteristics of the crack network (Fig. 7). This indicates that the anisotropy of mineral composition has a significant impact on the development of a rock crack network.

The clay content and the geometric parameters of the crack networks are compared and analyzed. It indicates that the kaolinite content in fault rocks negatively correlates with the quantitative values of geometric parameters as shown in Fig. 8. The SEM image shows that the crack width and connectivity of the upper and middle samples with higher content of minerals such as quartz are greater than those of the lower fault samples with higher kaolinite content (Fig. 5). The analysis shows that kaolinite is easy to fill in cracks, blocking and even closing the pores and cracks due to its
fine particle size. Kaolinite is a hydrophilic mineral with a certain plasticity when in contact with water. It is easy to smear and fill the primary cracks, increasing the sealing ability (Bense et al. 2013; Gui 2017).

Influence of clay content on the crack network of fault rock

Several investigations have confirmed the influence of clay minerals on fault weakening and sliding because clay minerals have different coefficients of friction compared to other minerals (Sperrevik et al. 2000; TerHeege et al. 2013; Vrolijk et al. 2016). Similar to the geometric parameters of the crack network, the coefficient of friction of a fault rock and fault gouge generally decreases with an increase in clay content (Fig. 9). The fracture form of the three samples in this paper accords with the three deformation mechanisms proposed by Lupini et al. (1981): (1) “turbulent mode”—when the clay content is less than 25%, the sample mainly undergoes brittle deformation of clastic particles in shear deformation. (2) “sliding mode”—when the clay content is higher than 70%, the sample is mainly composed of clay with low friction strength, and the fracture is mainly due to the rotational arrangement of low friction clay particles along the shear surface. (3) “transitional mode”—a combination of both turbulent and sliding shear.

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Fig. 8 Variation in crack network geometric parameters of the three samples with clay content: a Equivalent average connection number, b Crack density, and c Fractal dimension
It can be seen from Table 2 that the upper and middle samples are turbulent, especially the middle sample. These samples are composed primarily of minerals with high friction strength, such as quartz, and they are debris supported. The form of the crack network indicates brittle failure of this debris support under shear stress (Fig. 3b). The lower sample belongs to transitional shear, although it is close to sliding shear because the content of kaolinite is close to 70%. The relationship between the coefficient of friction and the crack network still needs to be further studied.

Cracks mostly emerge and grow along the gap between quartz particles or the clay fill between quartz particles. As shown in Fig. 10a, the distribution of quartz and other mineral particles in the fault rock samples has a relatively obvious boundary with the filling clay. Slender cracks mainly occur in the clay. In Fig. 10b, there is no obvious boundary between quartz particles and clay distribution. Some short but unconnected fine cracks are distributed around the main cracks, mainly developed in the clay. If these short cracks are disturbed, they can expand and increase the fracture degree of the rock.

According to fracture theory, the fracture toughness \( K_c \) of minerals is the actual resistance to crack extension (Irwin 1957). The stress-intensity factor \( K \) that causes crack extension can be expressed by Eq. 5. When \( K > K_c \), brittle fractures occur and the crack begins to extend.

\[
K = \lim_{r \to 0} \sqrt{2\pi r \sigma_{yy}(r, 0)}
\]  

Fig. 9 Coefficient of friction compared to clay content. Data from Lupini et al. (1981), Crawford et al. (2008), and Verberne et al. (2010)

Prediction of equivalent permeability on crack networks

In previous studies, there have been various prediction models for the equivalent permeability of crack networks (Lahiri 2021; Leung and Zimmerman 2012). However, due to the complexity of natural crack networks, available crack data is limited. The models in these studies have verified the accuracy of permeability estimation. The equivalent permeability in these estimation models is mainly composed of two parts, whether it is a natural or synthetic random crack network. One is the attribute of a single crack in the crack network,
which mainly focuses on the parameters such as crack length, width, surface roughness, and dip angle. The other is the characteristics of a crack network, such as connectivity, fractal dimension, etc. Based on this, this paper selects the equivalent permeability estimation model proposed by (Saevik and Nixon 2017), which considers the characteristics of the crack network and each crack:

$$K_{eff} = f \times \left( \frac{1}{A} \sum_{i=1}^{n} T_i L_i t_i \right)$$

(6)

where $K_{eff}$ is the equivalent permeability, $f$ is the crack connectivity, $T_i$, $L_i$, and $t_i$ are the transmittance, crack length, and tangential vector of the crack, respectively. $T_i$, $L_i$, and $t_i$ are not obtained in this study. Only the role of crack connectivity in determining equivalent permeability is described here.

According to the prediction model (Eq. 3), the connectivity of the upper and lower fault samples is 0, and the connectivity of the middle section is 0.435. Therefore, only the equivalent permeability of the middle section sample can be calculated according to Eq. 6, while the equivalent permeability of the upper and lower section samples is 0.

Conclusions

In this paper, a fault rock core uncovered by geological exploration holes was separated into three portions. The properties of the crack network in fault rock samples were investigated, and the main conclusions are given as follows.

(1) A nonuniformity coefficient is presented to describe the micro-crack network based on the mineral composition and the strength of mineral particles of fault rocks. In analyzing the crack networks, the nonuniformity coefficient produces satisfactory results. Despite the fact that geometric parameters have different meanings, it was revealed that these parameters are positively correlated in defining the crack networks in the three samples.

(2) The crack extension forms of three fault rock samples are different which is related to mineral particle fracture toughness. The results demonstrate that clay content is an essential factor affecting the crack extension in fault rock samples. When exposed to external force stress, cracks occur first in areas with low fracture toughness, such as clay infilling.

(3) The geometric parameters of the crack network have a negative connection with the clay content of fault rock. This pattern resembles the friction coefficient of fault rocks. The difference in the crack network of fault rock samples is thought to be connected to the friction coefficient of clay, although more research is needed.

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Declarations

Competing interests The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Bauer H, Schröckenfuchs TC, Decker K (2016) Hydrogeological properties of fault zones in a karstified carbonate aquifer (Northern Calcareous Alps, Austria). Hydrogeol J 24:1147–1170. https://doi.org/10.1007/s10040-016-1388-9

Benazzouz BK, Zaoui A (2012) A nanoscale simulation study of the friction coefficient of clay. Clay Clay Minerals 60:40–48. https://doi.org/10.1122/2011.12.028

Bense VF, Person MA (2006) Faults as conduit-barrier systems to fluid flow in siliciclastic sedimentary aquifers. Water Resour Res 42:1–18. https://doi.org/10.1029/2005wr004480

Bense VF, Gleeson T, Loveless SE, Bour O, Scibek J (2013) Fault Zone Hydrogeology. Earth Sci Rev 127:171–192. https://doi.org/10.1016/j.earscirev.2013.09.008

Bristow J (1960) Microcracks, and the static and dynamic elastic constants of annealed and heavily cold-worked metals. Brit J Appl Phys 11:81–85

Caine JS, Evans JP, Forster CB (1996) Fault zone architecture and permeability structure. Geology 24:1025–1028

Çifçi NB, Giger SB, Clennell MB (2013) Three-dimensional structure of experimentally produced clay smears: Implications for fault seal analysis3-D structure of clay smears. AAPG Bull 97:733–757

Cooke AP, Fisher QJ, Michie EAH, Yielding G (2018) Investigating the controls on fault rock distribution in normal faulted shallow burial limestones, Malta, and the implications for fluid flow. J Struct Geol 114:22–42. https://doi.org/10.1016/j.jsg.2018.05.024

Crawford BR, Faulkner DR, Rutter EH (2008) Strength, porosity, and permeability development during hydrostatic and shear loading of synthetic quartz-clay fault gouge. J Geophys Res 113:1–14. https://doi.org/10.1029/2006jb004634

Donnelly L (2006) A review of coal mining induced fault reactivation in Great Britain. Q J Eng Geol Hydroge 39:5–50

Eichhubl P, D’Onofro PS, Aydin A, Waters J, McCarty DK (2005) Structure, petrophysics, and diageneric of shale entrained along a normal fault at Black diamond mines, California—implications for fault seal. AAPG Bull 89:1113–1137

Gui H (2017) Impacts of Different Material Compositions on the Permeability of Fractured Fault Zone in Coal Measures. China University of mining and technology

Hamzehpour H, Mourzenko V, Thovert J-F, Adler P (2009) Percolation and permeability of networks of heterogeneous fractures. Phys Rev E 79:036302
Irwin GR (1957) Analysis of stresses and strains near the end of a crack traversing a plate. J Appl Mech 24:361–364
Jafari A, Babadagli T (2012) Estimation of equivalent fracture network permeability using fractal and statistical network properties. J Petrol Sci Eng 92–93:110–123. https://doi.org/10.1016/j.petrol.2012.06.007
Jiao CY, Hu Y, Xu X, Lu XB, Shen WJ, Hu XH (2018) Study on the effects of fracture on permeability with pore-fracture network model. Energ Explo Explor 36:1556–1565. https://doi.org/10. 1177/014539818777115
Ke CR, Jiang JL, Ge XR. Xiao BL (2011) Numerical simulation on influence of heterogeneity on macroscopic fracture process of rock failure. Chin J Rock Mech Eng 30:4093–4098
Kim YS, Peacock DC, Sanderson DJ (2004) Fault damage zones. J Struct Geol 26:503–517
Kushch V, Shmegera S, Sevostianov I (2009) SIF statistics in microcrack networks. Doctoral Dissertation, Tsinghua University
Li L (2015) Permeability of microcracked porous solids with random crack networks. Doctoral Dissertation, Tsinghua University
Luu VN, Murakami K, Samouh H, Maruyama I, Ohkubo T, Tom PP, Lupini J, Skinner A, Vaughan P (1981) The drained residual strength of sandstone. Rock Mech Rock Eng 14:61–87. https://doi.org/10.1016/01445987(81)90209-4
Litiwicz A (2006) Identification and quantification of cracks in concrete by optical fluorescent microscopy. Cem Concr Res 36:1508–1515. https://doi.org/10.1016/j.cemconres.2006.05.011
Liu XW, Liu QS, Liu JP, Wei L (2016) Experimental study on mechanism for fracture network initiation under complex stress conditions. Chin J Rock Mech Eng 35:3662–3670. https://doi.org/10.13722/j.cnki.jrme.2015.1544
Lupini J, Skinner A, Vaughan P (1981) The drained residual strength of cohesive soils. Geotechnique 31:181–213
Luu VN, Murakami K, Samouh H, Maruyama I, Ohkubo T, Tom PP, Chen L, Kano S, Yang H, Abe H, Suzuki K, Suzuki M (2021) Synthesis by solid state reaction of magnesium oxide and Mg-Chlorite. T Indian Ceram Soc 76:189–195. https://doi.org/10.1080/0371750x.2017.1327372
Pei Y, Paton DA, Knipe RJ, Wu K (2015) A review of fault sealing behaviour and its evaluation in siliciclastic rocks. Earth-Sci Rev 150:121–138
Robinson PC (1983) Connectivity of fracture systems—a percolation theory approach. J Phys a: Math Gen 16:605
Sævik PN, Nixon CW (2017) Inclusion of topological measurements into analytic estimates of effective permeability in fractured media. Water Resour Res 53:9424–9443. https://doi.org/10.1002/ 2017wr020943
Sanderson DJ, Nixon CW (2018) Topology, connectivity and percolation in fracture networks. J Struct Geol 115:167–177. https://doi. org/10.1016/j.jsg.2018.07.011
Sperrevik S, Førseth RB, Gabrielsen RH (2000) Experiments on clay smear formation along faults. Petrol Geosci 6:113–123
TerHeege J, Wassing B, Orlic B, Giger S, Clennell M (2013) Constraints on the sealing capacity of faults with clay smears from discrete element models validated by laboratory experiments. Rock Mech Rock Eng 46:465–478
Valentini L, Perugini D, Poli G (2007) The ‘small-world’ nature of fracture/conduit networks: possible implications for disequilibrium transport of magmas beneath mid-ocean ridges. J Volcanol Geoth Res 159:355–365. https://doi.org/10.1016/j.jvolgeores. 2006.08.002
Verberne BA, He CR, Spiers CJ (2010) Frictional properties of sedimentary rocks and natural fault gouge from the longmen Shan fault zone. Sichuan, China. B Seismol Soc Am 100:2767–2790
Vröljik PJ, Urai JL, Kettermann M (2016) Clay smear: review of mechanisms and applications. J Struct Geol 86:95–152
Walker RJ, Holdsworth RE, Armitage PJ, Faulkner DR (2013) Fault zone permeability structure evolution in basalts. Geology 41:59– 62. https://doi.org/10.1130/g33508.1
Xia HC, Wu AQ, Lu B, Xu DD (2021) Influence mechanism of heterogeneity on mechanical properties of rock materials. J Yangtze River Sci Res Inst 38:103–109
Yang SQ, Dai YH, Han LJ, Jin ZQ (2009) Experimental study on mechanical behavior of brittle marble samples containing different flaws under uniaxial compression. Eng Fract Mech 76:1833–1845
Zhang GP, Wei ZX, Ferrell RE (2009) Elastic modulus and hardness of muscovite and rectorite determined by nanindentation. Appl Clay Sci 43:271–281. https://doi.org/10.1016/j/clay.2008.08.010
Zhang YB, Xu YD, Liu XX, Yao XL, Wang S, Liang P, Sun L, Tian BZ (2021) Quantitative characterization and mesoscopic study of propagation and evolution of three-dimensional rock fractures based on CT. Rock Soil Mech 42:2659–2671. https://doi.org/10. 16285/j.rsm.2021.0339
Zhong ZB, Deng RG, Sun Y, Fu XM, Lv L (2017) Geometric characterization of natural crack network in rhyolite. Chin J Rock Mech Eng 36:167–174. https://doi.org/10.13722/j.cnki.jrme.2015.1730
Zhou CS, Li KF, Pang XY (2011) Effect of crack density and connectivity on the permeability of microcracked solids. Mech Mater 43:969–978

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