Pore pressure propagation in a permeable thin-layer coal seam based on a dual porosity model: A case of risk prediction of water inrush in coalmines

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Abstract. Thin-layer coal seams, a type of filling coal rock body, are considered aquifer systems made up of dual porosity medium with immediate floor. A numerical simulation for the pore pressure propagation along a thin-layer coal seam was carried out for the case of the Zhaogezhuang coalmine in China. By valuing the permeability ($K_f$) of the thin-layer coal seam, pore pressure variation with time was simulated and compared to the analytical solutions of a dual porosity model (DPM). The main conclusions were drawn as follow: (1) Seepage in the thin-layer coal seam was predominant in the whole process, and the distance of seepage was lengthened and the pore pressure decreased with increased $K_f$; (2) A series of simulated hydraulic graphs demonstrated that the pore pressure characteristics of peak-occurring and time-lag effects agreed with the analytical solutions of DPM; (3) By adjusting the parameters of DPM, two results of analytical solutions and numerical solutions fit well, particularly in the thin-layer coal seam; (4) The power law relationship between the peak-values and lag time of pore pressure were derived statistically under consideration of the $K_f$ parameter in the range of $10^{-8}$ to $10^{-10}$ m²/pa·s orders, and it was reasonable that the $K_f$ of the thin-layer coal seam was in the range of $10^{-8}$ m²/pa·s orders. The results were significantly helpful in decision-making for mining water prevention and prediction in practice.
1. Introduction
Recently, water inrush from a coal seam is commonly occurring water disaster that poses a serious threat to the safety of coal mining. The risk of water inrush from a coal floor layer causes geologists and the public great concern.

Usually, a series of initial or induced fractured spaces, such as fissures, sandwiched between thin layers and fault zones, are the main pathway for groundwater flow. Water inrush incidents occurring through these shortcuts generally have a certain “time-lag effect” [10, 11]. However, systematic research on pore pressure propagation preceding water inrush incidents, particularly in those exposed to subsurface open spaces, has not been conducted. According to recent studies, a coal seam intersecting with a fault zone might become a secondary pathway that conducts groundwater to subsurface open spaces [15].

In recent years, many research achievements regarding groundwater flow in fracture families have been accomplished. The studies generally concentrated on the seepage theory model of rock mass, such as the single fracture model (SFM) by Louis [5] and dual porosity model (DPM) by Barenblatt, et al. [1]. Onder [7] obtained analytical solutions of transient flow in a DPM by the Fourier transformation. Cornaton and Perrochet [2] derived a semi-analytical solution on the same issue using the Laplace transforms. Based on the in-depth hydraulic analysis of seepage through fracture networks, equivalent continuum, and dual porosity models, a comparative research project on seepage in different media models was summarized by Samardzioska and Popov [8].

In this paper, the study area is described by means of hydrogeology, boundary and initial conditions, and solution scheme in Section 2. A model that properly simplified and conceptualized the groundwater seepage process was established by embedding an aquifer system with a sandwiched thin-layer coal seam and fractured porous confining rock (buffer layer), as shown in figure 1. In Section 3, a series of numerical and analytical solutions are provided. The results of seepage evolution based on DPM analytical solutions are illustrated in Section 4. A comparison between simulated and analytical pore pressures was assessed in Section 5. Furthermore, a suite of statistic patterns of hydraulic characteristics acquired from simulation results and graphically presented in accordance with the correlation analysis between peak-values and lag-time of pore pressure are offered. Additionally, a novel strategy for risk prediction of water inrush in North China coalmines was proposed under consideration of the permeability of thin-layer coal seam as a parameter.
2. Establishment of numerical model

2.1. Hydrogeologic framework in study area

Zhaogezhuang Coalmine is located in the northeastern suburb of the Guye region, in the city of Tangshan, Hebei Province, China (figure 2). It covers an area of approximately 40 km$^2$, and features a semiarid climate, warm temperates, and distinct seasons. Mean annual precipitation is about 614.7 mm in the region. The surface covering is mainly composed of alluvial-eluvial deposits with a thickness of up to 40 m. As a result of the Neocathaysian structural system, a series of compression-shear folds and faults along the NNE direction occur alternately with representation of the main tectonic features of this area. Due to the influence of the local vortex structure, a small number of extensional folds and faults are emerging in the east wing of Kaiping syncline (the coalmine-hosting area of Kaiping coalfield).

![Figure 1. Conceptual scheme of the analytical model.](image)
The Zhaogezhuang coalmine is situated just at the Kaiping syncline’s tip, the end of the syncline axis turning sharply from N34°E to an almost E-W direction due to a strong squeezing and twisting tectonic stress (figure 2). The Ordovician Majiagou formation predominates the potentially flooding aquifer that is composed of thickly bedded and pale grey carbonate with a thickness of about 400 m. The aquifer hosts a thick sequence of upper Ordovician carbonates known as the Ordovician limestone aquifer [14].

The hydrogeologic framework model used in this study was based on stratigraphic and permeability data from the Kaiping Coalfield Basin (figure 3). There are a group of Carboniferous-Permian (C-P) strata that contain a series of coal measures beneath the basin. The Ordovician limestone aquifer is under a depth of 1300 meters and is separated by a confining unit (Bauxitic mudstone). The coal measures lie in the range of approximate 200 m thicknesses. The Ordovician limestone aquifers are the underlying formation of coal measure strata and are the main flooding aquifer in the study area. A typical comprehensive stratigraphic column of the Zhaogezhuang coalmine is depicted in figure 3. There exists a thin layer, named 1438 thin-layer coal seam, in the carboniferous formation. It is the ending segment of a seepage system consisting of a series of rock masses and fractures. Within this seepage system, the groundwater mainly comes from the Ordovician aquifer through the F8 fault zone and finally to the thin-layer coal seam [16].

**Figure 2.** Geological map of the Kaiping coalfield with locations of sites, strata, and tectonics mentioned in the text.
2.2. Solution schemes, boundaries, and initial conditions

The study site consisted of a segment of laneway located in the 14th level (-1225 m depth) in the Zhaogezhuang coalmine. The \(14_{35}\) thin-layer coal seam with 0.2-0.5 m thickness is hosted in a carboniferous formation and exposed out of the laneway on the lateral sides due to excavation, as shown in figure 4. It is not a water-bearing layer; however, when there is injection from a conductive fault zone nearby, it becomes a part of the seepage system by motivation of pore pressure propagation. Then, as the pressure accumulates, the water inrush incidents occur in time, as a case of small-scale water inrush ensued in the 13th level No.1 crosscut (-1100 m depth) in 2005 [16].

Figure 4 illustrates schematic maps of the model in which the main stratigraphic units and boundary conditions are discretized by grid elements with a scope of \(200 \times 100 \times 50\) m in a Cartesian coordinate system with a depth ranging from -1200 m to -1250 m. Two layers of aquitard strata, the immediate roof and immediate floor, called buffer layers in coalmining sciences, had 3.0 m thicknesses for convenience in this paper. The \(14_{35}\) thin-layer coal seam was sandwiched between two buffer layers. The buffer layers together with the \(14_{35}\) thin-layer coal seam formed the main body of the dual porosity (permeability) model (DPM). Furthermore, the body of the DPM was sealed by overlying and underlying impervious carboniferous fine sandstone, referred to as main roof and main floor in coalmining sciences, and each was 21 m thick. The top mechanic boundary of the model domain was loaded by 27.6 Mpa, which approximated the lithostatic pressure from the overlying strata.
In order to capture the pressure during the process of seepage, a series of observation points were set up at 10 m intervals along the DPM body.

**Figure 4.** Top diagram: Conceptual model; Bottom diagram: Numerical model of study area.

Based on long-term observation data, the maximum amplitude of groundwater level fluctuations was about 250 m, in the range of -260 to -110 m under the ground surface, approximately corresponding to 9.3 to 10.8 Mpa pressure in the study site at a depth of -1225 m. Considering the head loss in the process of seepage propagation along the fault zone, a specified-head boundary of the
lateral side in the scope of the DPM body was set to be 8.0 Mpa from beginning to end. The other sides of the model domain were set to be no-head and no-flux boundaries.

The numerical model was mainly composed of the following three types of rock material: (1) Impervious shaly sandstone, which were overlying and underlying the fissured coal seam sandwich, i.e. the DPM body; (2) Semipervious immediate roof and floor, which were sandstone, named buffer layers herein; and (3) Pervious \( \text{14}_{3S} \) thin-layer coal seam. The latter two comprised the DPM body in which the \( \text{14}_{3S} \) thin-layer coal seam was considered the fracture continuum and the buffer layer was the porosity continuum. The mechanical parameters of the medium materials are shown in Table 1. The hydraulic behaviors of seepage propagation along the DPM body was summarized in consideration of the \( K_f \) changes from \( 10^{-8} \) through \( 10^{-10} \) m\(^2\)/s, which was equal to \( 8.64 \times 10^0 \) to \( 8.64 \times 10^{-2} \) m/d.

**Table 1. Physical and mechanical parameters of rock mass.**

| Property                  | Shaly sandstone | Buffer layers | \( \text{14}_{3S} \) thin-layer coal seam |
|---------------------------|-----------------|---------------|------------------------------------------|
| Density /kg·m\(^{-3}\)   | 2600            | 2000          | 1500                                     |
| Elastic modulus/GPa       | 19.0            | 0.2           | 0.2                                      |
| Poisson ratio             | 0.24            | 0.25          | 0.4                                      |
| Cohesion /MPa             | 2.00            | 0.013         | 0.07                                     |
| Internal friction angle \(^{\circ}\) | 42              | 18            | 27                                       |
| Tensile strength /MPa     | 3.0             | 1.0           | 0.8                                      |

### 3. Theoretical basis

#### 3.1. Differential equations of dual porosity (permeability) model

As previously mentioned in Section 1, many valuable studies have been conducted on analytical solutions of unsteady flow in dual porosity models of rock mass. Two differential equations controlling two flows in the fracture and porosity continuum are described by the two diffusion equations below [1]:

\[
K_f \frac{\partial^2 p_f}{\partial x^2} = S_{sf} \frac{\partial p_f}{\partial t} - \alpha (p_m - p_f) \tag{1a}
\]

\[
K_m \frac{\partial^2 p_m}{\partial x^2} = S_{sm} \frac{\partial p_m}{\partial t} + \alpha (p_m - p_f) \tag{1b}
\]

where \( K_f \) and \( S_{sf} \) are the permeability and specific storage of the high-permeability medium (fracture), respectively; \( K_m \) and \( S_{sm} \) are the permeability and specific storage of the low-permeability medium (matrix), respectively; \( p_m \) and \( p_f \) are the hydraulic pressures (converted by hydraulic heads) of the matrix and the fracture, respectively; and \( \alpha \) is the water-exchanging coefficient.
Considering the equal water-exchanging term, the weakening of permeability in a matrix due to its small value and the weighting of fracture-porosity, can be expressed as follows:

\[
K_f \frac{\partial^2 p_f}{\partial x^2} = S_{sf} \frac{\partial p_f}{\partial t} + \beta S_{sm} \frac{\partial p_m}{\partial t} \tag{2a}
\]

\[
S_{sm} \frac{\partial p_m}{\partial t} = -\alpha (p_m - p_f) \tag{2b}
\]

If \( \phi \) is the fracture total porosity, then the matrix total porosity is \( 1 - \phi \); thus, the following is obtained:

\[
\phi = \frac{V_f}{V_t}, \quad 1 - \phi = \frac{V_m}{V_t}
\]

\[
\beta = \frac{1 - \phi}{\phi}
\]

where \( V_f \) is the fracture volume, \( V_m \) is the matrix volume, \( V_t \) is the apparent total volume, and \( \beta \) is the porosity ratio.

Subject to the boundary conditions, the following is obtained:

\[
p_f(0, t) = BC_1(t) \quad \text{or} \quad -K_f \frac{\partial p_f}{\partial x}(0, t) = BC_2(t), \quad \text{and} \quad p_f(+\infty, t) = 0
\]

and the initial conditions are as follow:

\[
p_f(x, 0) = p_m(x, 0) = 0
\]

### 3.2. Analytical solutions of dual porosity (permeability) model

The analytical solution of the problem was achieved by applying integral transformations successively with regard to space and time variables. After using the Laplace transformations and required inversion procedures, the solutions for hydraulic pressure of the fracture continuum were obtained as follow:

\[
p_f(x, t) = \frac{2P_f}{\sqrt{\pi}} \int_0^\infty \left[ \frac{S_{sf}}{2} \right] \frac{\exp(-\xi^2 - Y\beta\alpha)}{J_0(2\sqrt{At}/\sqrt{x})} d\xi \tag{3a}
\]

Finally, the solution for hydraulic pressure of the matrix continuum was as follows:

\[
p_m(x, t) = \frac{2P_m}{\sqrt{\pi}} \int_0^\infty \left[ \frac{S_{sm}}{2} \right] \frac{\exp(-\xi^2 - Y\beta\alpha)}{J_0(2\sqrt{At}/\sqrt{x})} d\xi \tag{3b}
\]

where \( A = Y\beta\alpha^2/S_{sm} \) and \( Y = x^2/4\xi^2K_f \), \( J_0(\cdot) \) is the zero-order Bessel function of the first kind.

The derivation of equations 3a and 3b were omitted here. There was a series of results from them, which were similar to previous analytical solutions of DPMs proposed by other literatures [6,7,9]. By adjusting the coefficients, such as \( K_f, S_{sf}, S_{sm}, \alpha, \) and \( \beta \), the seepage processes along the matrix
continuum were calculated with equation 3b. The seepage processes along the fracture continuum obtained with equation 3a were characterized by the occurrence of obvious pressure peaks. The following numerical simulation demonstrated the phenomenon.

4. Results of simulation studies

4.1. Features of pore pressure propagation during seepage evolution
As shown in figure 5, a group of seepage evolution nephograms along the fissured coal sandwich are illustrated at three phases of pore pressure propagation from three simulated scenarios. Permeability was determined by assigning $K_p$, i.e. $10^8$ m$^2$/pa·s, $10^9$ m$^2$/pa·s, and $10^{10}$ m$^2$/pa·s. The simulated pore pressure durations were recorded automatically by the history function embedded in the FLAC$^{3D}$ software. Some typical phenomena were as follow:
Figure 5. Nephograms of simulation of pore pressure propagation and fluid flow of seepage evolution corresponding to various scenarios in terms of $K_f$: (a) $10^{-8}$ m$^2$/pa·s, (b) $10^{-9}$ m$^2$/pa·s, (c) $10^{-10}$ m$^2$/pa·s.

The following observations were made according to the nephograms in figure 5 above:
• From the flow vectors, seepage evolved mainly along the 143s thin-layer coal seam. The nephogram of pore pressure was the shape of a cluster of ‘flames.’ The pore pressures within the ‘flame core’ were higher than the surroundings. The pore pressures were descent steeply over the transition between two media, i.e. thin-layer coal seam and the buffer layer. It was also observed that there were water exchanges between two media, especially in the later time period (more than 500 days), and the exchanges increased in scope and intensity under the circumstance of each simulated scenario.

• In the thin-layer coal seam, at early time periods (less than 100 days), the pore pressures in the flow inlet nearby were higher, e.g. maximum pressure up to about 6.0 Mpa (figure 5c), and decreased gradually over time. As a result, the curve’s slopes of pore pressure duration varied from steep towering to gentle sloping with the progression of time. Eventually, it was seen that the curves became a flat slope along the seepage pathway in the intermediate phase (about 500 days) and final phase (around 1,000 days) (figures 5a-5c). Permeability determined the pore pressure magnitude and the dissipation speed.

• With decreased permeability of the 143s thin-layer coal seam, it was observed that the pore pressure levels rose and conversely, the distance of seepage decreased. For example, the maxima of water pressure at the 10 m location were 1.91 Mpa, 1.84 Mpa, and 1.31 Mpa, corresponding to the three scenarios of \( K_f \), \( 10^{-8} \) m²/ pa·s, \( 10^{-9} \) m²/ pa·s, and \( 10^{-10} \) m²/ pa·s, respectively. The phenomenon relative to the permeability could potentially prevent water inrush disasters if the correlation between them could be discovered.

In short, seepage mainly occurred in the 143s thin-layer coal seam. The pore pressure levels and the seepage distance depended upon the value of the permeability coefficients in the fissured rock sandwich. These phenomena were simulated effectively by the numerical model in which the fluid-mechanical interaction embedded function in FLAC\textsuperscript{3D} was applied by tuning a few mechanical (table 1) and hydraulic parameters.

4.2. Hydraulic characteristics of pore pressure duration

According to \( K_f \) values, a series of pore pressure duration curves along the 143s thin-layer coal seam and buffer layers were illustrated successively (figures 6a-6c) by exporting their historical records of pore pressure determined by hypothetical history points in the numerical model of FLAC\textsuperscript{3D}. Some hydraulic characteristics were concluded as follow.
Figure 6. Curves of pore pressure duration of seepage evolution in different locations along the 1438 thin-layer coal thin and buffer layer corresponding to the various scenarios in terms of $K_f$: (a) $10^{-8} \text{ m}^2/\text{pa-s}$; (b) $10^{-9} \text{ m}^2/\text{pa-s}$; (c) $10^{-10} \text{ m}^2/\text{pa-s}$. 
Referring to the figures above, the following observations were made:

- In the 143S thin-layer coal seam, there were obvious peak values in every pore pressure duration curves; however, they were less obvious in the buffer layers. Accordingly, the pore pressure duration curves presented a series of leptokurtic-shape lines with heavy tails in the nearby inlet (closer than 10 m) or platykurtic shapes at a distance (longer than 30 m) for the whole simulation period.

- The closer to the inlet of 143S thin-layer coal seam, the higher the pore pressure peak values and, as a result, the shorter the peak-occurring time lag period. Every group of pore pressure peak value in a scenario showed a descending trend along the thin-layer coal seam. In the segments of depletion, i.e. the intermediate or final phase, the pore pressure duration curves gradually slowed down in either the thin-layer coal seam or the buffer layer.

- The results of simulation indicated that the time-lag effects of the pore pressure peaks appeared successively in the 143S thin-layer coal seam. Whether the time lag period of pore pressure peaks in each of historical points was postponed mostly depended upon the variations of $K_f$ value. Generally, with a lower $K_f$ value, the peak-occurring lag times were delayed.

5. Analysis and discussion

5.1. Comparison of numerical and analytical solutions

Using the results obtained by numerical simulations, a series of pore pressure graphs of the 143S thin-layer coal seam (filling fracture medium) showed obvious peak-occurring and time-lag effects, which did not appear or were less obvious in the buffer layers (porosity medium).

In comparison to many existing analytical [6] or semi-analytical solutions [2] using DPMs, the novel solutions performed better for a variety of challenging parameter fields, including $K_f$, $K_m$, $S_{sj}$, $S_{sm}$, $\beta$, $\phi$, and structural and hydraulic parameters of rock mass. By tuning these parameters, the analytical results were very close to the simulated results, which were only obtained by valuing the mechanical and hydraulic parameters in the numerical model. Estimations of the fitting results in the various simulated scenarios were assessed by means of the root-mean-square error (RMSE), computed as follow:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (P_{\text{sim},i} - P_{\text{anal},i})^2}{n}} \quad (4)$$

where $n$ is the total number of moment of the discretized time domain, $P_{\text{sim},i}$ is the simulated pore pressure at the $i$-th moment, and $P_{\text{anal},i}$ is the analytical pore pressure at the $i$-th moment.

Figure 7 illustrates the fitting results in which the RMSE was regarded as the evaluation index. It can be seen that the fitting results of 143S thin-layer coal seam, RMSE 0.025 to 0.084 MPa, were better than that of the buffer layer, RMSE 0.065 to 0.121 MPa. Hydraulic parameters for various scenarios used in the analytical solutions of DPM are shown in Table 2.
The results of the analytical solutions of the DPM provided accurate and analytical representations of peak-occurring and time-lag effects. This may have been caused by the following: (1) By use of Bessel function, the analytical solutions were more reasonable from a technical point of view; (2)
More impacting factors were parameterized in the form of coefficients, such as $K_f$ and $K_m$, $S_{sf}$ and $S_{sm}$, $\alpha$, $\beta$, $\phi$ and so on. These parameters provided powerful capability and flexible options for fine tuning the shape of calculated curves. Therefore, the results obtained by the analytical solutions were more flexible and likely to achieve the desired fitting effects. Of course, they should correspond to reality.

### Table 2. Hydraulic parameters used in the analytical solutions of DPM.

| Scenario | Parameters | Values |
|----------|------------|--------|
| **Scenario 1** | Permeability in 143S thin-layer coal seam ($K_f$) | $1.0 \times 10^{-8}$ m$^2$/pa·s |
| | Storage in 143S thin-layer coal seam ($S_{sf}$) | $1.0 \times 10^{-0.15}$ MPa$^{-1}$ |
| | Storage in buffer layer ($S_{sm}$) | $1.0 \times 10^{-3.82}$ MPa$^{-1}$ |
| | Exchange coefficient ($\alpha$) | $1.0 \times 10^{-6.06}$ m$^2$ |
| | Porosity-weighting coefficient ($\beta$) | $1.0 \times 10^{2.6}$ |
| **Scenario 2** | Permeability in 143S thin-layer coal seam ($K_f$) | $1.0 \times 10^{-9}$ m$^2$/pa·s |
| | Storage in 143S thin-layer coal seam ($S_{sf}$) | $1.0 \times 10^{-0.15}$ MPa$^{-1}$ |
| | Storage in buffer layer ($S_{sm}$) | $1.0 \times 10^{-3.0}$ MPa$^{-1}$ |
| | Exchange coefficient ($\alpha$) | $1.0 \times 10^{-6.44}$ m$^2$ |
| | Porosity-weighting coefficient ($\beta$) | $1.0 \times 10^{3.87}$ |
| **Scenario 3** | Permeability in 143S thin-layer coal seam ($K_f$) | $1.0 \times 10^{-10}$ m$^2$/pa·s |
| | Storage in 143S thin-layer coal seam ($S_{sf}$) | $1.0 \times 10^{-0.32}$ MPa$^{-1}$ |
| | Storage in buffer layer ($S_{sm}$) | $1.0 \times 10^{-3.88}$ MPa$^{-1}$ |
| | Exchange coefficient ($\alpha$) | $1.0 \times 10^{-4.85}$ m$^2$ |
| | Porosity-weighting coefficient ($\beta$) | $1.0 \times 10^{3.74}$ |

Through the analysis of several occurrences of typical lagging water inrush incidents at different depths in the past decade, i.e., No. 1 crosscut in the 9th level (approximately -730 m in 1972) [12] and in the 13th level (almost -1100 m in 2005) [13], it was found that the groundwater dynamics in both hydraulic discharge rate and water pressure presented a declining trend in the five-year observation period [17]. Examples are as follow: (1) The hydraulic discharge from 0.15 m$^3$/min to 0.10 m$^3$/min; and (2) The in-situ monitored water pressure from 4.0 Mpa to 2.0 Mpa. However, some problems arose while analyzing the in-situ monitoring hydraulic graph. First, the in-situ monitored water pressures contributed by both porosity and fracture seepages were mixed and undistinguishable from each other. Second, because of the lack of knowing when and where a water inrush incident will occur, it could be speculated that a peak value along the hydraulic graph should appear in the initial phase over which the in-situ hydraulic graphs are impossible to be recorded thereby. Notably, the fact that the occurrence of peak values exist is an important clue for water-inrush predictions, which is worth
investigating for issues of mining security. The numerical model approach provides a promising and feasible solution to solving these problems. Meanwhile, novel analytical solutions are worth considering as a testing approach to verify the precision and reasonableness of numerical simulation solutions.

5.2. Correlation analysis of hydraulic behaviors for risk prediction of water inrush

A reasonable estimation of the permeability coefficients should be determined before risk prediction of water inrush is carried out. In reference to previous studies [3, 4], the permeability $K_f$ range of 0.06 to 3.72 m/d was proposed. After all, it is reasonable that the permeability coefficient of the 143S thin-layer coal seam is at the range of $10^{-8}$ m$^2$/pa·s order of magnitude.

There exists a relationship between the pore pressure peak-value and peak-occurring lag time by considering the hydraulic coefficients as parameters such as $K_f$, $K_m$, and so on. As a case study, the correlation patterns of hydraulic characteristics under the influence of $K_f$ were analyzed. By varying the value of $K_f$ from $10^{-7}$ to $10^{-9}$ m$^2$/pa·s, the correlation between the pore pressure peak value and peak-occurring lag time was obtained based on $K_f$ as an impacting parameter. Ultimately, the power law relationship between them can be found statistically. The results are shown in Figure 8.

![Figure 8. Correlation between the pore pressure peak value and the peak-occurring lag time within the range of $10^{-7}$–$10^{-9}$ m$^2$/pa·s orders of magnitude of $K_f$.](image-url)
### Table 3. Risk prediction chart of critical time for water inrush along the fissured coal sandwich.

| Distance /m | Permeability $K_f$ /m$^2$·(pa·s)$^{-1}$ | Pore pressure peak value /Mpa | Peak-occurring lag time /day | Critical time for water inrush prevention /day |
|-------------|----------------------------------------|------------------------------|------------------------------|-----------------------------------------------|
| 10          | 1.96                                   | 8.1                          | 8.1                          | 8.1                                           |
| 20          | $10^{-8}$                              | 0.98                         | 16.1                         | 24.2                                          |
| 30          | 0.62                                   | 36.2                         | 60.4                         |                                                |
| 40          | 0.43                                   | 51.6                         | 87.8                         |                                                |

The data of figure 8 can be applied to risk prediction of water inrush to demonstrate a schematic example for practical application. A risk prediction chart for critical time for water inrush prevention along a fissured coal sandwich corresponding to the $K_f$ as $10^{-8}$ m$^2$/pa·s order of magnitude is provided in Table 3. This approach can be applied in any coalmine with potential risks of water inrush occurring.

### 6. Conclusions

This paper conducted simulation analyses of the seepage evolution along the 143S thin-layer coal seam with pore pressure propagation in an assumed DPM. The pattern of pore pressure propagation was related to the permeability of the rock mass and agreed well with the analytical solution proposed by this paper. By considering the $K_f$ as a parameter, the correlations between pore pressure peak-value and peak-occurring lag time were derived statistically and applicable to risk prediction of water inrush events. With the efforts made in this paper, the following conclusions were drawn.

- Seepage mainly took place in full-filled fractures, i.e. 143S thin-layer coal seam. The phenomenon of longer seepage distance and lower pore pressure occurred in the process with increased values of $K_f$.
- The pore pressure graph simulated in the 143S thin-layer coal seam had obvious hydraulic characteristics of peak-occurring and time-lag effects instead of the porous medium, which was representative of the buffer layers. With increased $K_f$, the time-lag effect became more remarkable. By assessing with RMSE value, the simulated results matched well with the theoretical calculated results using analytical solutions proposed by the DPM.
- There was a significant correlation between pore pressure peak-value and peak-occurring lag time. The power law relationship between them was found statistically within the range of $10^{-8}$ to $10^{-10}$ m$^2$/pa·s orders of $K_f$.
- In accordance with the previous study, the $K_f$ of the 143S thin coal-seam was within the range of $10^{-8}$ m$^2$/pa·s, and it corresponded in reality to the Zhaogezhuang coalmine. A scheme for risk prediction of water inrush was tabulated and proved applicable in decision-making for risk prevention and prediction in practice.
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