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TECHNICAL ARTICLE

An Improved Vulnerability Assessment Model for Floor Water Bursting from a Confined Aquifer Based on the Water Inrush Coefficient Method

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Abstract Pressurized confined water below coal seams are serious threats to mining. The conventional water inrush coefficient method fails to accurately assess the risk of floor water inrush under some specific conditions, such as high water pressure and low water yield in the source aquifers. Large amounts of water inrush data including water inrush flow rate, water inrush coefficient (T_s), floor aquiclude thickness (M), and water abundance, were collected and statistically analyzed. The results indicated that inrushes mostly occurred when M was less than 30 m and that the critical T_s increased linearly with M. The occurrence of a water inrush and water inrush yield amount (Q in L/s) were related to both the values of T_s and the unit water inflow (q in L/(s m)). In addition, 97.7% of the large- and medium-sized inrush events occurred when $q > 2$ L/(s m) and only a small proportion (3.2%) of the small-sized inrushes happened when $q < 0.1$ L (s m). T_s, M and q were comprehensively analyzed and used to evaluate vulnerability to floor water inrush. By analyzing the distribution of water inrush points and the scale of water inrush events, the vulnerability was divided into four levels (safe, moderately safe, potentially dangerous, and highly risky) based on T_s–M and T_s–q models. Successful application of these models in the Huaibei mining area proved that they are feasible in practice. The T_s–M and T_s–q charts can be used independently or jointly. These new methods should improve the accuracy of predictions and evaluations during deep exploitation where the aquifers are often characterized with high pressure but low water abundance. The results could also help reduce the amount spent on mine water prevention and control.

Keywords Water hazards · Coal mining · Unit water inflow · Aquiclude thickness

Introduction

More than 90% of China's coal mines are seriously threatened by pressurized confined water below the coal seam (Li et al. 2015; Shi and Singh 2001; Wu et al. 2011). More significantly, the hydrogeological conditions become increasingly complicated as mining is extended to greater depths (Coalfield Geological Central Bureau of China (CGCBC) 2000; State Administration of Coal Mine Safety of China (SACMSC) 2009; Zhou and Li 2001; Hu et al. 2014). Scientific prediction and evaluation of water inrush is urgently needed to reduce the occurrence of accidents and the expense of unnecessary protective measures (Qiao et al. 2014).

Floor water bursting from underlying confined aquifers has been studied for over 80 years, for in the 1930s, Slesarev studied the failure mechanism of coal seam floor and deduced formulas to calculate the safe water pressure and floor thickness by assuming that the floor behaved like a beam fixed at both ends (Gao 2013; Wang and Liu 2007). The water inrush coefficient (T_s), defined as the water

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pressure that can be sustained by the unit aquiclude thickness of the coal seam floor, was first put forward at the Jiaozuo Mine Water Control Conference in 1964 (Liu 2009). Since then, the method has experienced two major revisions and developments (Liu 1981; Zhou 1997). In 1979, the effect of mine pressure on the aquiclude was incorporated into T_s for the first time, and the thickness of the mining-induced fissure zone (C_P), which is typically measured by in-situ water pressure testing, was advised to be subtracted from the total aquiclude thickness (Guan 2012). The second revision introduced the strength ratio coefficient (SRC) for different rock layers by considering the relationship between the water-resisting ability of each rock layer and its strength (Qiao et al. 2009; Yao et al. 2012). The water inrush coefficient method has been widely used to predict and assess floor water inrush risks. However, it is not accurate under some specific conditions, such as when the underlying aquifers have high water pressure and low water yield properties, conditions that are being encountered more frequently as mining depth increases.

Various vulnerability assessment theories and methods for assessing floor water inrush have been developed, including the: “down three perturbed zones theory (water-conducting fractured zone, waterproof zone, confined water up-flowing zone)” (Li 1999); key-strata theory (Qian et al. 1996); nonlinear model (Yang et al. 2005); strong seepage theory (Ye and Liu 2005); seepage-flow conversion theory (Qiao et al. 2013); fractal theory (Wang et al. 2017); numerical and analog simulation methods (Kuznetsov and Trofimov 2002; Yin et al. 2016; Zhang et al. 2014); and various laboratory experiments (Pang et al. 2014; Yu et al. 2016). Together, these laid the foundation for systematic acquisition of hydrogeological parameters and evaluation of water inrush risks.

In addition, many methods have been developed to address the limited accuracy of the water inrush coefficient method, including the: “three-maps-two predictions” method (Wu et al. 2007); vulnerable index method (Wu et al. 2009); artificial neural network (ANN) (Wu et al. 2015); geographic information system (GIS) and grey relational analysis (GRA) (Qiu et al. 2017; Wu et al. 2008); analytic hierarchy process (AHP) method (Li et al. 2015; Wu et al. 2017); fluid–solid coupled numerical model (Chen et al. 2017); and damage-based hydromechanical model (Zhu and Wei 2011). Also, factors that influence inrushes, such as the thickness of the floor aquiclude, rock mass integrity and expansive limits, and anti-permeability strength, have been studied (Duan et al. 2012; Meng et al. 2012; Wang et al. 2012; Wu et al. 2017). However, few have researched the effect of specific capacity on water inrush through the mine floor (Qiao et al. 2009) and the relationship between the thickness of the aquiclude and its water-resisting ability per unit thickness.

The conventional water inrush coefficient method is not very appropriate for deep exploitation. In this study, a large volume of data was collected and analyzed to develop the relationships between floor water inrush vulnerability and water inrush coefficient (T_s), unit water inflow (q), and aquiclude thickness (M) to construct T_s–q and T_s–M assessment charts to evaluate floor water inrush vulnerability in deep exploitation.

Limitations on Using the Water Inrush Coefficient

The conventional water inrush coefficient method is based on statistical analysis of long-term inrush data and stipulated in *Regulation for Coal Mine Water Prevention and Control, China* (SACMSC 2009). The water inrush coefficient is expressed as an empirical formula:

$$T_s = \frac{P}{M} \tag{1}$$

where T_s is the water inrush coefficient (MPa/m), P is the water pressure sustained by the coal seam floor (MPa), and M is the thickness of the coal floor aquiclude (m). The formula applies to both coal mining and tunneling (Wu et al. 2013).

As indicated by SACMSC (2009), inrushes tend not to occur if water inrush coefficients are less than 0.06 MPa/m in areas with geological structures and less than 0.10 MPa/m in areas without geological structures. Otherwise, the areas are considered to be prone to inrushes.

Since T_s accounts for some of the characteristics of the underlying aquifer and aquiclude, it has played a key role in floor water inrush vulnerability assessment. Meanwhile, the formula (Eq. 1) is not only simple, but practical as well. Results from the inrush coefficient method are generally consistent with actual conditions when exploitation safety is evaluated at water pressures less than 3 MPa. However, mining is now taking place at depths up to 1200 m (Wu et al. 2017) with water pressures that range from 7.3 to 13.0 MPa. Consequently, the calculated inrush coefficient ranges from 0.144 to 1.256 MPa/m, while the limit for safe exploitation is 0.06–0.1 MPa/m (SACMSC 2009).

However, as shown in supplementary Table 1, at some panels where T_s was higher than 0.10 (e.g. panel 91002 of the Chazhuang Coal Mine in Feicheng, $T_s = 0.16$ MPa/m for the Ordovician limestone; panel 10404 of the Baizhuang Coal Mine, $T_s = 0.17$ MPa/m for the Ordovician limestone; panel N7109 in the Guozhang Coal Mine in Zibo, $T_s = 0.48$ MPa/m for the 4th Taiyuan limestone; and panel 142 of the Langquan Coal Mine in Zibo mine zone, $T_s = 0.18$ MPa/m for the Ordovician limestone), the inrush amounts were small during actual exploitation. In addition, no inrushes occurred at panel III616 in the Huaibei

Yangzhuang Coal Mine ($T_s = 0.11$ MPa/m for the 1st, 2nd, and 3rd Taiyuan limestone, where $M = 50.0$ m) and panel 1088 in the Zibo Xiazhuang Mine ($T_s = 0.14$ MPa/m for the Ordovician limestone, where $M = 50.9$ m), even though T_s exceeded the safe range, due to the presence of a thick aquiclude. However, large inrush accidents have occurred at panels where q was large and M was small (see No. 9 and 10 in supplemental Table 1).

The conventional water inrush coefficient method only considers the aquifer's water pressure, whereas the unit water inflow (q) of the aquifer is neglected. In addition, the effective thickness of the aquiclude is not given enough consideration. When the Ordovician, Taiyuan, and Xu limestone strata are at greater depths, fracture development is often poor, resulting in small unit water inflow, poor aquifer connectivity under confined pressure conditions, and consequently few, if any, inrushes. Even with a high T_s value, the probability of an inrush was still very small when the effective thickness of the aquiclude was very large. Thus, the possibility of an inrush cannot just be considered to be a simple reciprocal relationship with the effective aquiclude thickness. The critical water inrush coefficient changes with the aquiclude thickness.

Water Inrush Assessment Based on T_s–M and T_s–q

T_s–M Model

The mining areas in eastern China such as Jiaozuo, Zibo, Feicheng, and Huaibei (Fig. 1), have been exploited for over 40 years. The water inrush sources are the Ordovician, Taiyuan, and Xu limestone aquifers, which underlie the coal seams. In earlier times, the water pressure of the limestone on the mining panels were generally less than 3 MPa because of the shallow mining depths, with most ranging from 1 to 2 MPa. The limestone water pressure increases with depth, and mining under high confining pressures can cause damage to the mine floor. If the intrusion height of the limestone was also counted, the calculated inrush coefficient would far exceed the upper limit stipulated in the *Standard for Exploration and Evaluation of Hydrogeology, Engineering Geology and Environment Geology in Coal Beds and Coal Mine Water Prevention and Control Regulations* (State Administration of Work Safety of China (SAWSC) 2008; SAWSC and SACMSC 2009).

There might be severe floor water inrushes in other mining areas with thin aquicludes, even if the water inrush coefficient is less than the critical values of 0.06 and 0.10 MPa/m. The statistics of 328 inrush cases in eastern China (Jiaozuo, Zibo, Feicheng, and Huaibei mining areas) are presented in Supplemental Table 2. A scatter plot was made to analyze the relationship between the inrush vulnerability and water inrush coefficient, with effective aquiclude thickness (M) as the abscissa and water inrush coefficient (T_s) as the ordinate (Fig. 2). The points of panels with inrushes are mainly distributed in areas where the thickness of the coal floor aquiclude was less than 30 m. The proportion of water inrush points with $M < 30$ m and $T_s < 0.06$ MPa/m is 48.3%, nearly half of the total cases. Further, water inrush still occurred when the inrush coefficient was as low as 0.012 MPa/m, much less than the suggested critical value. The floor aquiclude thickness of panels without an inrush mainly ranged from 30 to 80 m, and accounted for 98.9% of all non-water inrush panels.

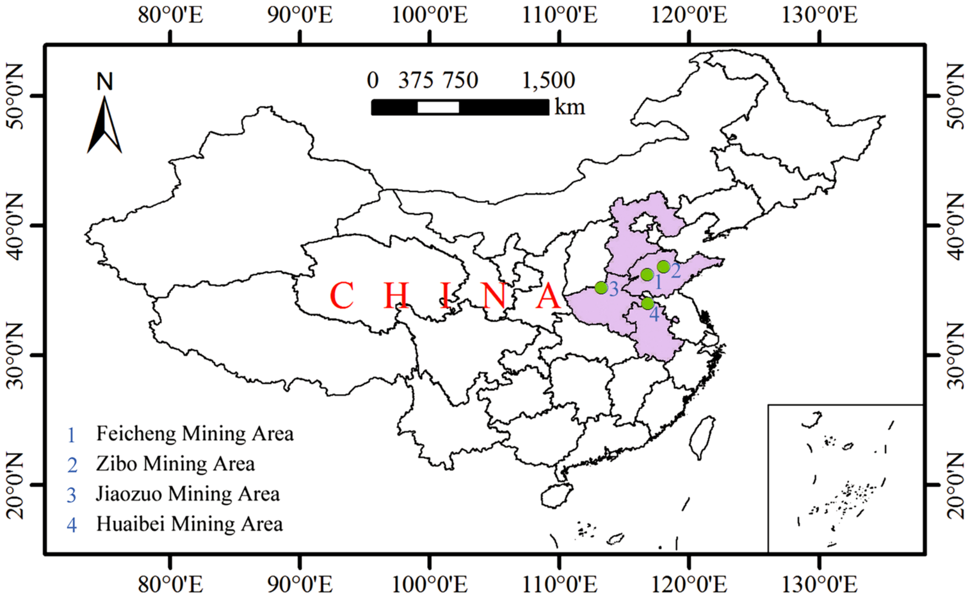

Fig. 1 Locations of Jiaozuo, Zibo, Feicheng, and Huaibei mining areas, in eastern China

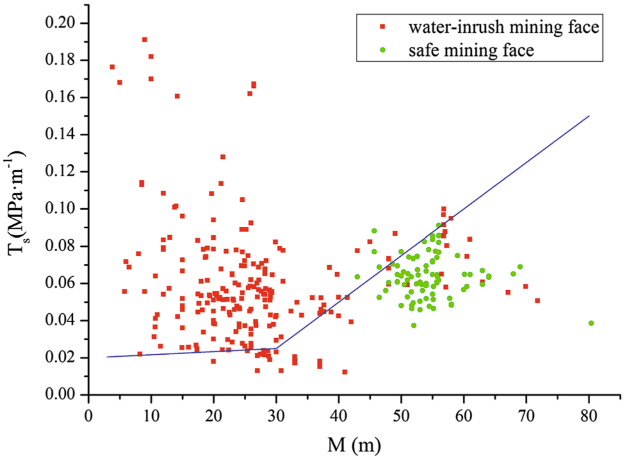

Fig. 2 T_s–M characteristic scatter plot of inrush points in the Jiaozuo, Zibo, Feicheng, and Huaibei mining areas

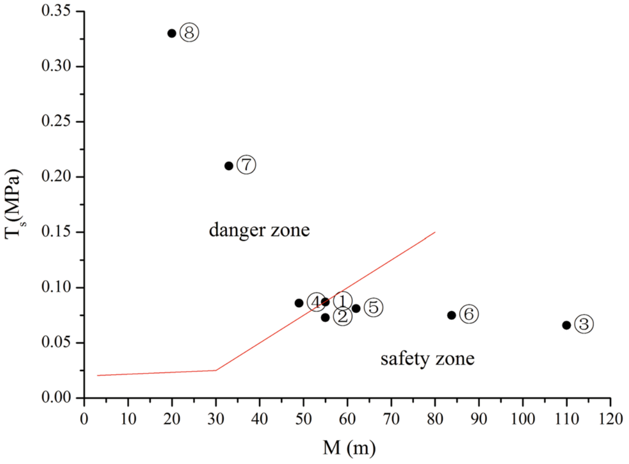

Fig. 3 T_s–M model evaluation diagram to evaluate the vulnerability to floor water inrush and its application

Even though there were faults in panels where the aquiclude thickness was over 80 m and the water inrush coefficient exceeded the critical value of 0.06 MPa/m, no inrush events occurred. These indicate that the water inrush vulnerability is closely related to the aquiclude thickness. Mines with thinner aquicludes are more vulnerable to water inrushes.

Mining-induced pressure damage to the floor and original fractures in the aquiclude can cause floor water inrushes when the aquiclude is thin. As the aquiclude thickness increases, the existence of a sufficient protective layer is critical in resisting floor water invasion. For a specific panel, at a constant coal seam thickness, mining depth, and crustal stress, the floor damage zone and original progressive intrusion height are determined by the "down three perturbed zones theory". A thicker floor aquiclude provides better protection, and vice versa. The critical inrush coefficient would exceed the suggested 0.06 MPa/m with greater floor aquiclude thickness and can be expressed with the linear relationship: $T_{s,c} = \alpha M + \beta$. The relationship between critical inrush coefficient $T_{s,c}$ and M can be expressed by the following:

$$T_{s,c} = \frac{1}{6000} M + 0.02, \qquad \text{where } 0 < M \leqslant 30 \text{ m} \tag{2}$$

$$T_{s,c} = 0.0025M - 0.05, \qquad \text{where } 30 < M \leqslant 80 \text{ m} \tag{3}$$

Hence, the water inrush assessment method can be represented by Fig. 3, of which the abscissa is the floor aquiclude thickness and the ordinate is the floor water inrush coefficient. The straight lines represent the critical water inrush coefficients and divide the graph into a safe zone and a water inrush zone. Thus, the assessment of floor water inrush at any panel can be predicted by projecting the M and T_s values onto Fig. 3.

T_s–q Model

For an inrush to occur in a coal panel, a water source and flow path(s) are required. To take the extreme case, an aquifer can be considered to be an aquiclude when it contains no water, making an inrush unlikely, even when the inrush coefficient exceeds the critical value. In deep mines, crustal stress increases with depth, resulting in fracture closure, a decrease in the specific capacity of the karst aquifer, and poor karst water dynamics and karst development. So, the amount of water in fractured karst aquifers decreases with depth (Qiao et al. 2009). As a result, inrushes were not observed in some places where the critical water inrush coefficient was clearly exceeded. Data describing 216 water inrush cases in the Feicheng, Jiaozuo, and Zibo mining areas were collected (Fig. 4), and statistically analyzed. The relationship between inrush vulnerability, water inrush coefficient, and aquifer water abundance was systematically analyzed to construct the T_s–q water inrush assessment chart.

Table 1 presents an analysis of the 216 inrush cases (Fig. 4), consisting of 87 minor inrushes (inflow rates ≤60 m^3/h), 114 medium inrushes (inflow rates between 60 and 600 m^3/h), and 15 major events (inflow rates >600 m^3/h). There were few inrush events when $T_s < 0.04$ MPa/m. There was no water inrush at $T_s < 0.01$ MPa/m. Major and medium inrushes mainly occurred when $q > 2$ L/(s m), accounting for 97.7% of the total major and medium inrush cases. Minor inrushes occurred when $0.1 < q < 2$ L/(s m). Few minor inrush events, accounting for 3.2% of the total, were observed when $q < 0.1$ L (s m).

As shown in Fig. 4, most of the minor inrush points were on the left side of the straight line $q = 2$ L/(s m) and

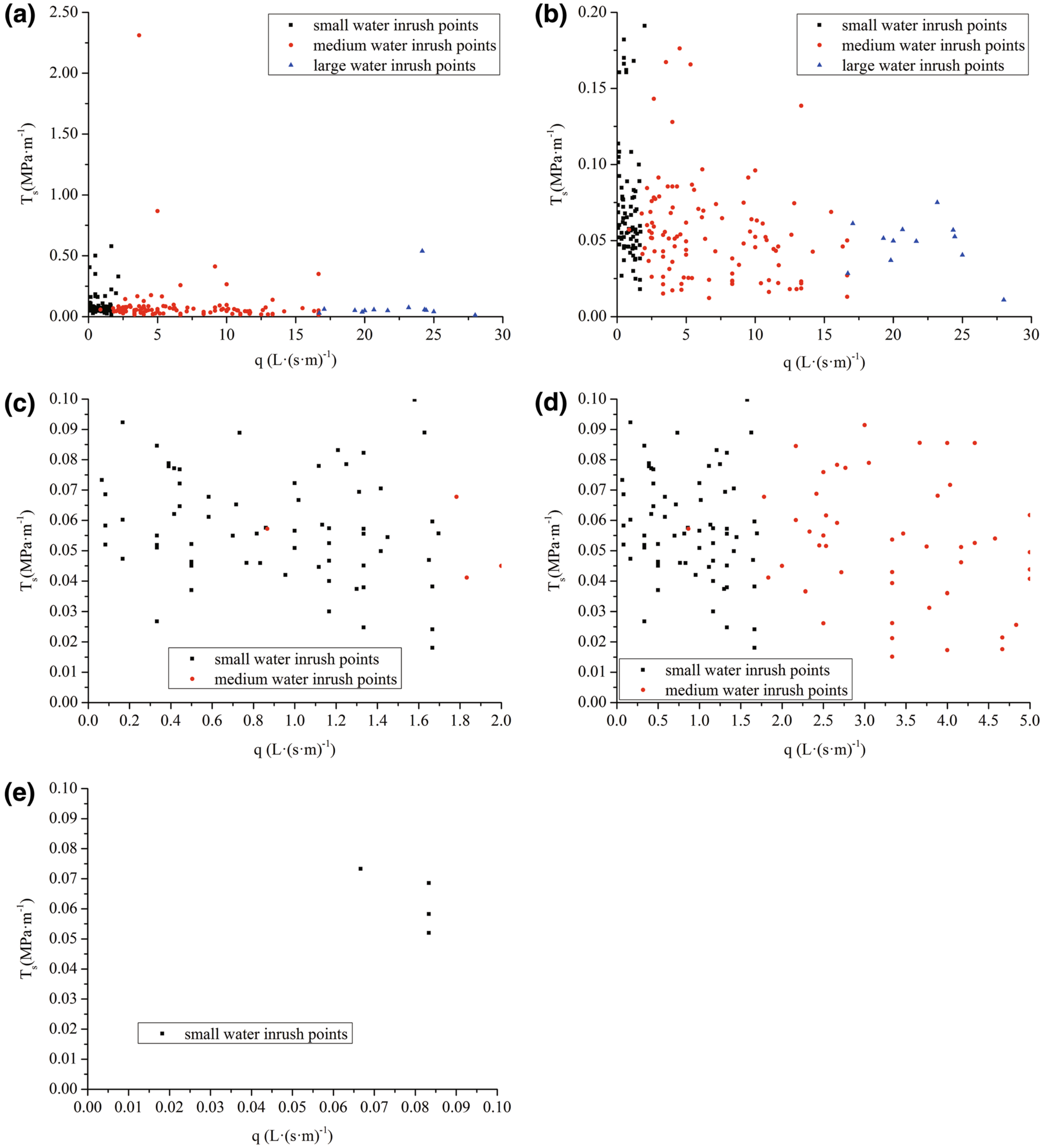

Fig. 4 T_s–q characteristic scatter plot of water-inrush points in the Jiaozuo, Zibo, and Feicheng mining areas, where **b, c, d**, and **e** were obtained by controlling horizontal and vertical coordinates of **a** over different ranges

the water inrush points corresponded mainly to T_s values ranging from 0.00 to 0.25 MPa/m. Inrush inflow was less when the abscissa values were closer to zero. Only a few minor inrush events occurred when $T_s < 0.04$ MPa/m. Similarly, when $q < 0.1$ L (s m), there were few inrush cases, and there were none when $q < 0.06$ L (s m). When $T_s < 0.04$ MPa/m and $q > 2$ L/(s m), more medium water inrushes occurred, whereas there were few inrush events when $T_s < 0.01$ MPa/m. This is because high crustal stress results in fracture closure and therefore low water

Table 1 Statistics of water inrush data in three mining areas

Inrush characteristics	Small water inrush points ($Q \leq 60$ m^3/h)	Medium water inrush points ($60 < Q < 600$ m^3/h)	Large water inrush points ($Q > 600$ m^3/h)
$T_s < 0.04$ MPa/m	4.2%	15.3%	1.4%
$T_s < 0.01$ MPa/m	0	0	0
$q > 2$ L/s m	0.5%	51.4%	6.9%
$q < 0.1$ L/s m	3.2%	0	0
$0.1 < q < 2$ L/s m	36.6%	1.4%	0
$q > 10$ L/s m	0	13%	6.9%
Total	40.3%	52.8%	6.9%

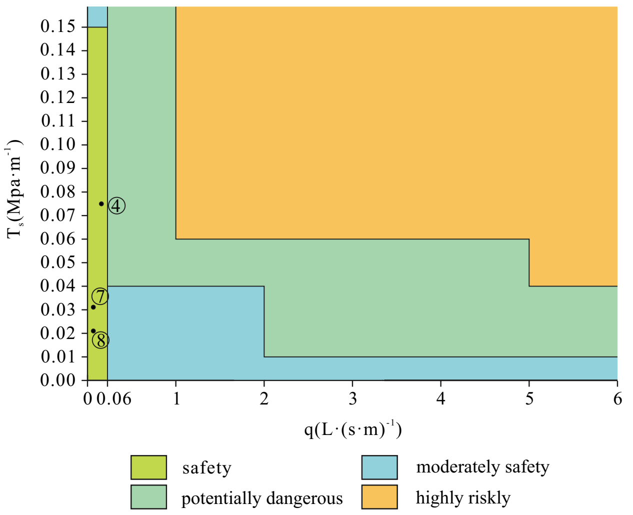

Fig. 5 Model evaluation diagram of T_s–q to evaluate the vulnerability to floor water inrush and its application

abundance. Crustal stress increases as depth increases and is in a linear relation with the water pressure of the fractured karst aquifer. Under the same aquiclude conditions, deep coal seam exploitation demonstrated a significantly greater inrush coefficient than shallow exploitation, but less water in the aquifer.

Based on the distribution of water inrush points, the scale of water inrushes, and the above analysis, a risk assessment model of floor water inrush was established (Fig. 5). The risk was graded into four classes: safe, moderately safe, potentially dangerous, and highly risky. In the T_s–q chart, the ordinate is the water inrush coefficient and the abscissas is the unit water inflow of the aquifer. By combining the abundance index (q) of the aquifer with the calculated inrush coefficient of the mine area, one can project site-specific data onto Fig. 5 and thus approximate the inrush vulnerability of the area based on the positions of the points in the figure.

Application of T_s–M and T_s–q in Huaibei Mining Area

In the Huaibei mining area, which is located north of Huaihe, Anhui Province, China (Fig. 1), the No. 10 coal seam was exploited with floor altitudes from −637.4 to −455.0 m in the Taoyuan, Yangliu, Yuandian, Zhuxianzhuang, and Liudian mines. The aquifer consists of the Taiyuan Formation limestone, while the aquiclude directly under the coal seam comprises a massive mudstone interbedded with fine siltstone, with strong water resistance. The floor water pressures were between 3.0 and 6.89 MPa.

Eight panels were selected (Table 2). According to the T_s–M assessment chart, the polygonal line of Equations (2) and (3) was drawn onto Fig. 3. Then, the T_s and M values of the panels were projected to the graph. Points above the line represent panels have a risk of water inrush, and those further from the line are more at risk. Figure 3 shows the T_s–M assessment results of the panels in the Huaibei mining area.

The current standard critical water inrush coefficient in the Huaibei Mining Group is 0.07 MPa/m. From Table 2 and Fig. 3 it can be seen that, of the above eight panels, only panel 10414 of the Yangliu mine had a water inrush coefficient less than the critical value. The other seven panels had excessive inrush coefficients. Despite this, according to the T_s–M method, safe exploitation was determined for panels: ①1023 and ②1024 of the Taoyuan II Mine, and ⑤1034 and ⑥ 1036 1 of the Zhuxianzhuang II Mine. There was a risk of water inrush found for panels: ④1021 of the Yuandian No. 1 Mine, and the ⑦1044 and ⑧1037 of the Liudian Mine. In other words, these three panels have a risk of water inrush according to both the current water inrush coefficient method and the T_s–M method. However, since the Archaean Eon limestone aquifer q index or the maximal water discharge in boreholes were very small for these three panels, the T_s–q method was used for further assessment.

The modified parameters for panel 1021 of the Yuandian No. 1 Mine were $T_s = 0.075$ MPa/m and

Table 2 Results of T_s, T_s–M and T_s–q methods to evaluate the vulnerability to floor water inrush of some working face in Huaibei mining area; in all cases, the water source was the Taiyuan limestone (Ls)

Working face (WF)	Water source strata	M(m)	q(L/s m)/Q (m^3/h)	T (MPa/m)	T method	T_s–M model	T_s–q model
No. 1023 WF of Taoyuan II mine	1st and 2nd Taiyuan Ls	55	–/3	0.087	Vulnerable	Safe	Safe
No. 1024 WF of Taoyuan II mine	1st and 2nd Taiyuan Ls	55	–/20	0.073	Vulnerable	Safe	Safe
No. 10414 WF of Yangliu mine	4th Taiyuan Ls	110	–/20	0.066	Safe	Safe	Safe
No. 1021 WF of Yuandian I mine	1st and 4th Taiyuan Ls	49	0.0098–0.045/--	0.086	Vulnerable	Vulnerable	Safe
No. 1034 WF of Zhuxianzhuang II mine	1st and 2nd Taiyuan Ls	62	0.012–0.013/--	0.081	Vulnerable	Safe	Safe
No. 1036 WF of Zhuxianzhuang II mine	3rd and 4th Taiyuan Ls	83.8	0.012–0.013/--	0.075	Vulnerable	Safe	Safe
No. 1044 WF of Liudian mine	1st and 2nd Taiyuan Ls	33	0.00014–0.024/60	0.21	Vulnerable	Vulnerable	Safe
No. 1037 WF of Liudian mine	1 and 2nd Taiyuan Ls	20	0.0054–0.024/--	0.33	Vulnerable	Vulnerable	Safe

-- indicates that the corresponding data is missing or was not collected

$q = 0.0098$–0.045 L (s m). The modified parameters for panel 1044 of the Liudian Mine were $T_s = 0.033$ MPa/m, and $q = 0.00014$–0.024 L (s m); the borehole maximal water discharge was 60 m^3/h. For panel 1037 of the Liudian Mine, the modified parameters were $T_s = 0.023$ MPa/m and $q = 0.0054$–0.024 L (s m). These points were plotted in the T_s–q chart (Fig. 5). It can be concluded that although both the water inrush coefficient method and the T_s–M method indicated a risk of water inrush, they were still safe due to the small aquifer q value, according to the results of T_s–q method.

According to the current standard of the Huaibei Mining Group, seven of the eight selected panels were vulnerable to floor water inrush. However, the T_s–M and T_s–q methods indicated that all seven panels could be safely mined. In fact, all eight panels were safely mined and a cumulative total of 3.44 million tons of raw coal were produced. Thus, the feasibility of the T_s–M and T_s–q methods were demonstrated in the Huaibei mining area for the Archaean Eon limestone aquifer floor with its high confined pressure and weak water abundance.

Results and Discussion

T_s–q Model

The new model inherits the easy usability of the conventional T_s method, and, more significantly, provides a more accurate prediction of the risk of water inrush. The T_s–q model takes the inherent property (q) of the aquifer into account, while the conventional T_s method does not consider this property. The method can explain, from the perspective of the water inrush source, the phenomena of large inrushes with low T_s and high q, and no inrushes with high T_s and low q. The vulnerability for floor water bursting was assessed correctly by the new method. Furthermore, water control measures can be recommended in response to each risk level. For example, no pre-treatment is necessary in safe areas but in high risk areas, many essential techniques or means need to be implemented or mining needs to cease. By projecting site-specific data on the T_s–q chart, coal mine technicians can predict the risk of water inrush easily and quickly and take relevant water inrush control measures to reduce unnecessary project costs.

Given the fact that most of the water inrush data collected from practice were medium or small sized, the distribution of large water inrush points is not clear enough. However, based on the available statistical data, the scale on which the medium water inrush points were gathered can be approximated with a polyline, which could be extrapolated when a security coefficient is considered. Areas out of the polyline were known as high risk areas where large or extremely large water inrush occurred. The issue can be better resolved by adding more large inrush data. In addition, the borders of these four risk zones were based on the inrush data collected from the Feicheng, Jiaozuo, and Zibo mining areas. Though the model was applied successfully in the Huaibei mining area, more practical water inrush data is needed to verify and modify the accuracy of the zones.

T_s–M Model

The T_s–M method incorporates the linear relationship between T_s and M. The method explains why there is still water inrush in panels with small M when T_s is much less than the critical value of $T_s = 0.1$ Mpa/m. It also provides a more accurate evaluation method of water inrush prediction for t mines similar to the Huaibei mines where panels are characterized by a thick aquiclude under the floor.

In mines or panels whose $M < 30$ m, the T_s–M method is more accurate. For mines with an aquiclude thickness that exceeds 50 m, the T_s–M method has greatly enhanced the critical T_s value. This new method provides greater critical T_s and allows some mines to produce safely. The correlation results of T_s–M method have been applied and promoted in the Huaibei mining area and the method is now included in the 'Water Control and Prevention Standard of Huaibei Coal Mining Group' as an internal specification for the company. The T_s–M method provides both a theoretical foundation for floor water control and prevention and practical guidance for coal mines in China and other regions that are affected by water inrushes.

The effective thickness of the aquiclude (M) has been considered in the T_s method, but it's not sufficient, as concluded in this paper: the critical condition of water inrush does not remain constant but varies with the value of M. The probable cause of this phenomenon might be the incremental improvement of unit thickness water-resistance caused by the increase of M. However, experiments are still necessary to verify this corollary. Similar to the T_s–q method proposed in this paper, it could be applied successfully in the Huaibei mining area because of all of the available data. The T_s–M method may require more practical cases to test and correct the zone values.

As demonstrated above, more reasonable predictions can be accomplished by combining unit water inflow (q) and the effective thickness of the aquiclude (M) into the conventional T_s method. By observing how the critical T_s value changes at different M values from the view of floor water inrush pathways, one can conclude that thicker aquicludes indicate greater critical T_s values. The T_s–q method is also based on the inrush sources, considering the aquifer's water pressure and abundance. The possibility and flow of an inrush increases when the aquifer contains more water. The two methods above can improve the accuracy of predictions of the risk and likely severity of water inrushes.

Conclusions

1. Water inrush flow rate (Q), water inrush coefficient (T_s), the effective thickness of the aquiclude (M), and the water abundance in aquifers were collected for 544 water inrush events. Statistical analysis of the data indicated that areas where the floor aquiclude thickness was less than 30 m were prone to inrushes. Due to the incremental improvement of the unit water-resistance, the critical T_s was not constant but increased linearly with M, as expressed by the following mathematical expressions: $\frac{1}{6000}M + 0.02$ (when $0 < M \leq 30$ m) and $0.0025M - 0.05$ (when $30 < M \leq 80$ m). So, it is inappropriate to simply make the critical T_s a constant between 0.06 and 0.1 MPa/m. The critical T_s should vary with the thickness of the aquiclude.
2. Our results show that the possibility and flow rate of water inrush are related to both the traditional T_s, and the amount of water in the aquifer (represented by unit inflow q). 97.7% of the large or medium-sized inrushes occurred when $q > 2$ L/(s m), whereas small inrushes occurred mainly when $0.1 < q < 2$ L/(s m). There were only a few small inrush events, approximately 3.2% of the total inrushes, when $q < 0.1$ L (s m).
3. The T_s–M and T_s–q evaluation models were established as improvements to the conventional water inrush coefficient method. The water inrush coefficient, effective aquiclude thickness, and unit water inflow are the main factors that should be used to evaluate the vulnerability of floor water inrush. Based on the distribution of inrush events and the flow of water inrushes on the T_s–M and T_s–q charts, the vulnerability was divided into four levels: safe, moderately safe, potentially dangerous, and highly risky.
4. Successful application of these evaluation charts in the Huaibei mining area proved that they are effective. Workers can determine risk levels with these two charts, independently or jointly, by simply projecting the site-specific data on the charts. These methods solved major problems with the conventional T_s method, such as insufficient evidence, the amount of work required, and the high cost of inrush control, and enhanced the accuracy of predictions and assessment for deep mining inrushes in situations characterized by high water pressure but relatively little water.

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