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Design of Water Barrier Pillar for Safety in Underground Coal Mines

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Abstract

Mine inundations are a known risk, although their cause is unknown. When active workings are near water-logged old workings in an underground coal mine, significant inrush or water seepage can cause massive loss of life and property. As a precaution, a water barrier pillar of adequate width is left un-mined between these two workings throughout the life of mine. Mine safety depends on the stability of the water barrier pillar width. Therefore, a rational method for designing the water barrier pillar must be considered. There are empirical and numerical approaches for designing and assessing water barrier pillars. Indian water barrier pillars employ empirical tools with many drawbacks. Unlike empirical methods, numerical methods are more realistic and help in explaining water barrier pillar behaviour under different stress-seepage circumstances. This study develops a numerical model using the Finite Element Method code RS2. It uses the governing parameters for designing safe water barrier pillars in underground coal mines. This research will help in evaluating the design of the water barrier pillar and identify its failure mechanisms. This research examines a hydro-mechanical coupled plain strain softening model to assess the water flow characteristics of a water barrier pillar. It has been noted that water pressure exerted on the barrier pillar increases the yield zone width inside the barrier pillar, resulting in diminished stability of the water barrier pillar.

Keywords

Mine Inundations, Numerical Modelling, Water Seepage Mechanism, Hydro-mechanical Coupling, Coal Pillar Design

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1 Introduction

The open-cast coal reserves are rapidly diminishing, making underground mining the only possibility for the future of the coal mining sector. The number of underground mines and their contribution to yearly coal production will progressively rise in the forthcoming years by using closed and abandoned mines to reach the inaccessible underground coal seams.

The risk of water influx from abandoned mine workings must be taken seriously since more underground coal mines are anticipated to commence operations, and current underground activities are projected to increase. This problem occurs particularly in situations where operating and potential coal mines are situated near rivers, opencast mines, water bodies (jore/nallah), abandoned workings, and tailings repositories and when unfavourable climatic circumstances may result in rapid flooding of the mine (Bringemeier 2012). Insufficient sealing of antiquated boreholes, erroneous face drivage, unmarked boreholes in the underground plan, overlooked water hazard plans, inadequate or malfunctioning pumps, proximity to geological disturbances, surface cracks and fissures, subsidence, excessive rainfall, water barrier failures, restricted sump area, water dam failures, and the existence of abandoned or waterlogged workings elevate the risk of inundation (Tripathy and Ala 2018).

A coal pillar with a rational width should be positioned at the property border to serve as a water barrier. The width of this pillar should not be compromised for increased mineral recovery. In most underground coal mines, either too much or too little coal is left in the barrier between the active and old water-logged mines.

The empirically designed coal pillar for mine safety considers only the pressure from overlying strata. It performs the function of isolation and load bearing, but the coal pillar should also consider mine pressure and problems like water pressure, seepage, and reliability (Wang et al. 2023). The water inrush flow mechanism is non-linear and hard to quantify. However, numerical methods are more realistic for water barrier pillar flow analysis. Numerical methods are more practical and ideal for designing barrier pillars with an edge over traditional empirical and physical modelling methods.

1.1 Stability of barrier pillar

The effectiveness of the water barrier pillar is crucial for ensuring mine safety and protecting the mine environment. Consequently, it ought to be formulated to preserve long-term stability. The overall width of the yield zones is a clear indication of the stress level, as shown in Fig. 1 (Yang et al. 2023). In contrast, the elastic core's width indicates the barrier pillar's remaining ability to support the additional load. Thus, these two measurements aid in identifying the likelihood of a structural breakdown in a barrier pillar. Therefore, the elastic ratio is suggested to assess a barrier pillar's long-term stability, as shown in Eq.1.

$$R_e = \frac{W - W_y}{W_y} \tag{1}$$

Where, R_e is the Elastic Ratio, W is the Width of the Water barrier pillar, W_e is the Width of the elastic zone, and W_y is the Width of yield zones.

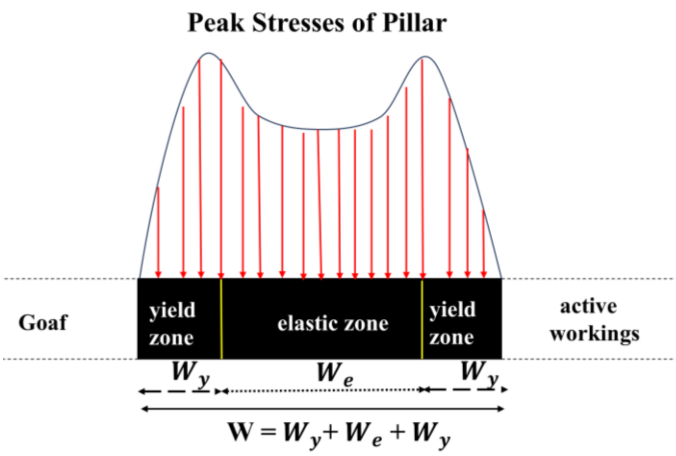

Fig. 1 Various widths across the barrier pillar due to the re-distribution of stresses.

For a water barrier pillar to be stable, R_e must be greater than or equal to 1. When water pressure acts across the WBP, there is an increase in the width of the yield zone (Luo et al. 2001), which leads to a decrease in the stability of the pillar. The dry state's elasticity ratio is higher than the wet condition (Wong et al. 2016).

Mine inundation accidents have continued sporadically despite improved safety practices and technological measures in recent decades. There are instances where a barrier of adequate dimensions failed to prevent a substantial influx of water from an adjacent inundated mine owing to geological irregularities. In the context of Indian coal mines, many case studies indicate that 60-meter pillars collapse due to significant water heads and discontinuities, necessitating the maintenance of such width in accordance with regulatory standards. There is a need for a novel approach to evaluate the effectiveness of a water barrier pillar to optimise the design of the coal water barrier pillar while maintaining safety standards.

Consequently, a numerical model is developed using the Finite Element Code RS2 in this research. The model incorporates many governing factors to elucidate the water flow process via a water barrier pillar. The model can replicate stress distribution, water infiltration, and its effect on pillar strength with increasing water levels. A comprehensive hydro-mechanical model is established based on the physical representation of a mine to simulate water flow via a water barrier pillar.

2 Methodology

For the scope of this research activity, the authors used a specific framework of factors to get a highly representative evaluation. The analyses were performed for two scenarios regarding mechanical and coupled hydro-mechanical models at an overburden depth of 100 m. The Mohr-Coulomb constitutive model was used to simulate the roof and floor, whereas Hoek and Brown used the coal layer.

Models were created to represent a horizontal seam with coal pillars with a large width-to-height ratio, such as the pillars in coal mines. Model geometries were developed in RS2, a finite element code developed by using the geological properties (Agioutantis et al. 2022; Vlachogiannis and Benardos 2023; Rocscience 2024). The water pressure acting across the coal seam and strata above and below it, along with hydraulic properties, which change its behaviour, is shown in the model (Smith et al. 2019; Zevgolis et al. 2022). The size of the water barrier pillar and the working pillar was based on Coal Mine Regulation 2017 (DGMS (Tech) Circular no. 5 2003; CMR 2017), which acts as a barrier between the water-logged goaf and active workings. Firstly, a mechanical model is simulated to represent the mines, comprising the floor, water barrier pillar, and roof. To simulate this pillar system in RS2, a suitable number of zones have been assigned in the software for the analysis. Material properties were assigned to depict the different bedding planes in these zones, as shown in Table 1, Table 2, and 3. The model assumed competent roof, floor, and typical coal properties for the pillar. The model is subdivided into various stages. Then, the model is subjected to a virgin stress condition, meaning no excavations are in the equilibrium stage. Following the excavation of a 50-meter-wide goaf and a 4.8 m gallery to construct the water barrier pillar of width 60 m. Furthermore, an extraction of 4.8 m of the gallery in the coal seam led to the formation of a 30 m wide coal pillar in the active workings. Various models were initially tested using elastic block constitutive behaviour. The model size is 153 m x 179.60 m, as shown in Fig. 2. Mechanical equilibrium was achieved before subjecting the models to a water pressure gradient. A coupled hydro-mechanical model was built to analyse the behaviour of the water barrier pillar after establishing mechanical equilibrium and applying hydraulic properties to the model. The geotechnical conditions were evaluated to determine the pathways of water flows and strength. The stress within the barrier pillar and the impact of water flow on the barrier were also assessed. The water pressure varies for a particular width of the pillar. The effect of these variations on the strength and stability of the pillar is observed and noted down. The stress within the barrier pillar and the impact of water flow on the barrier were also assessed. The behaviour of the coupled hydro-mechanical model is simulated at different stages.

This research uses a coupled methodology based on Biot consolidation. This approach incorporates drained analysis, allowing for the movement of water into and out of the model, resulting in variations in total volume. A fluctuation in water level induces seepage-related pore pressures and stress-induced excess pore pressure, which dissipates over time, leading to consolidation and a subsequent reduction in pillar stability (Rocscience 2024).

Table 1 Material properties for the Mohr-Coulomb Constitutive Model

Layer	Unit weight (MN/m3)	Young's Modulus (MPa)	Peak Tensile strength (MPa)	Peak Cohesion (MPa)	Peak friction angle	Material Type	Permeability, Ks m/s
Sandstone (Roof)	0.024	13390	5.32	2.1	40	Elastic	8e-09
Sandstone (Floor)	0.024	13390	5.32	2.1	40	Elastic	8e-09

Table 2 Material properties for the Hoek-Brown Constitutive Model

Layer	Unit weight (MN/m3)	Young's Modulus (MPa)	Compressive strength (MPa)	m_b parameter	s parameter	m_b parameter	s parameter	Material Type
Coal	0.018	2000	10	1.47	0.007	1	0.001	Plastic

The permeability of coal is taken as 2.57e -08 m/s.

Table 3 Material properties for the interface element

Parameter	Value
Interface normal stiffness (MPa/m)	100000
Interface shear stiffness (MPa/m)	50000

The in situ vertical stresses can be estimated using Equation 2. Also, the horizontal stress, σ_H is 0.33 times the vertical stress. Gravitational loading using field stresses was used in the model.

$$\sigma_v = \gamma H \tag{2}$$

Where, σ_v is vertical stresses acting on the pillar, γ is the unit weight of rock, H is the depth of coal working.

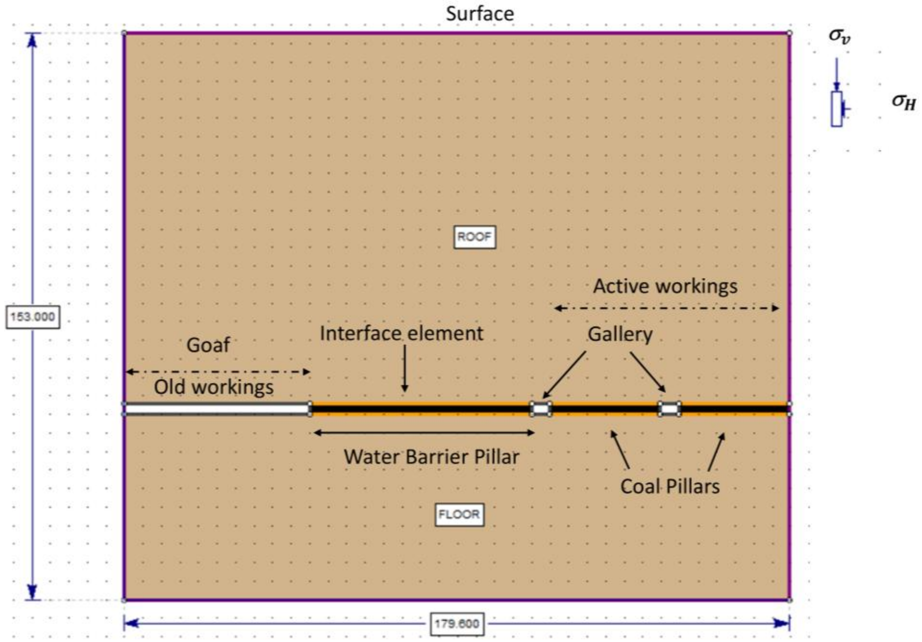

Fig. 2 The water barrier pillar separating goaf and active workings.

Water from various sources seeps into the goaf and accumulates there. The water pressure from pooled water in the goaf exerts pressure across the water barrier pillar. A water pressure of 0.5 MPa acting across the barrier along the goaf side is shown in Fig. 3 a). Due to the seepage of water across the barrier, it destabilises the pillar and causes more yielding and a decrease in its stability, as shown in Fig. 3 b).

Water flow occurs along the pillar, roof, floor, and the interface between the roof and coal, as well as coal and floor.

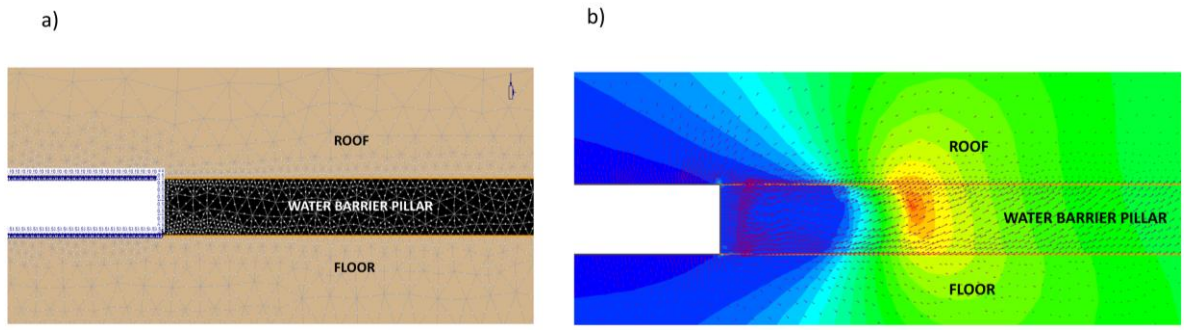

Fig. 3 The water barrier pillar separating goaf and active workings a) Water pressure acting across the barrier of 60 m width and b) water seepage across the barrier pillar, roof and floor.

In RS2, the groundwater seepage analysis employs the same mesh used in the stress analysis. Seepage analysis is conducted before stress analysis to ensure that the computed pore pressures may be used in the stress analysis.

3 Results and Discussion

The results of the mechanical model and the coupled hydro-mechanical model based on the physical model of a mine for a barrier pillar of width of 60 m located at a depth of 100 m, having a pillar height of 3 m, were analysed. A mechanical model, in which no groundwater flow influence was considered, and another model where hydraulic properties coupled with the mechanical model of the mine are used for the simulation of barrier pillar behaviour for varying water pressures. The elasticity ratio of the coupled hydro-mechanical pillar was compared with a mechanical model of the water barrier pillar.

Excavation in a coal seam causes stress redistribution, shifting the load to adjacent pillars and creating a yield zone. This yield zone typically forms across the pillar. Similarly, developing galleries transfers stress to neighbouring pillars. A dry coal barrier pillar can create a yield zone, especially near a goaf. For example, a 50-meter goaf near a water barrier pillar can induce a yield zone within the pillar itself (see Figure 4).

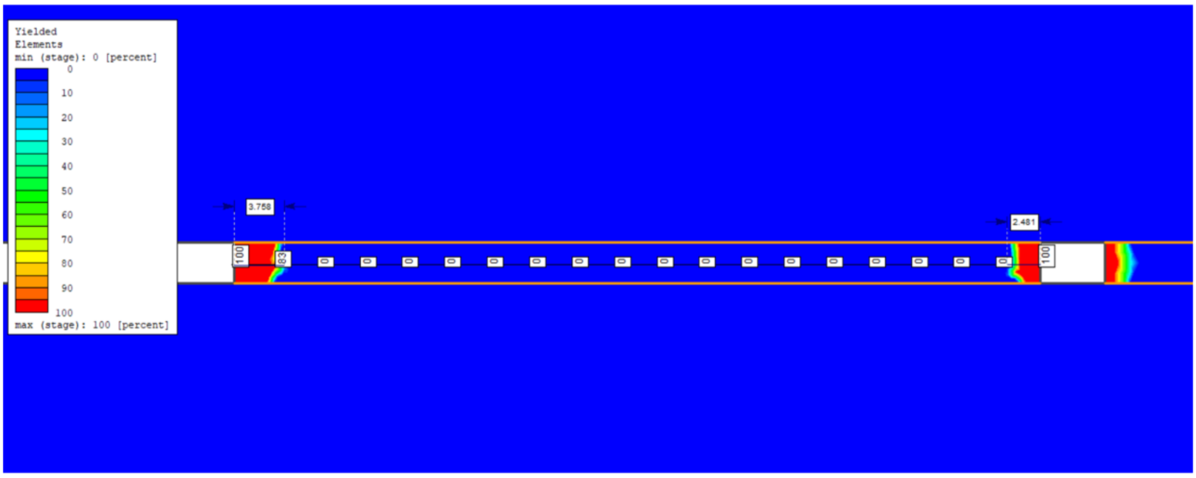

Fig. 4 Yield zone in a water barrier pillar in dry condition.

The width of the yield zone and elastic zone can be utilised to determine the stability of the water barrier pillar. The total width of the yield zone in a 60 m wide coal pillar comes to around 6.24 m. Using equation 1, the stability of the water barrier pillar in dry conditions comes to 8.61, which means the pillar is stable since there is no water present in the goaf. For a pillar to be stable, the elasticity ratio must be more than or equal to 1. A high stress concentration can be seen along the goaf side. The stress acting on the barrier pillar in dry conditions is shown in Fig.5.

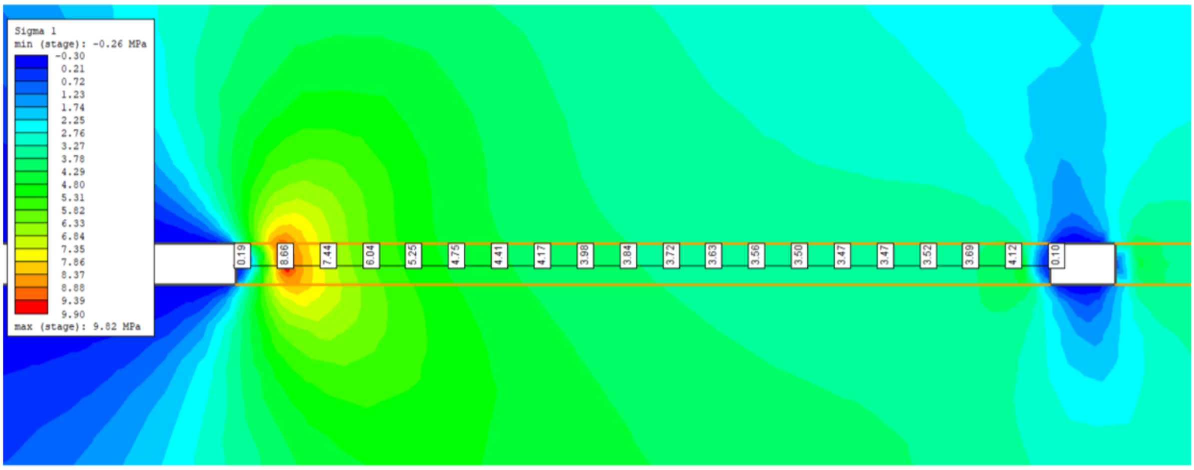

Fig. 5 The Stresses over the water barrier pillar in dry condition.

After introducing the water pressure across the coupled hydro-mechanical model of the water barrier pillar, the yield zone's width increases when the water flows across it. The width of the yield zone will be higher as compared to the initial mechanical model in dry conditions, as shown in Fig.6. With the help of equation 1, the stability of the water barrier pillar is calculated to be 6.54, which indicates that the pillar is getting unstable when there is water present in the goaf with a water pressure of 0.1 MPa.

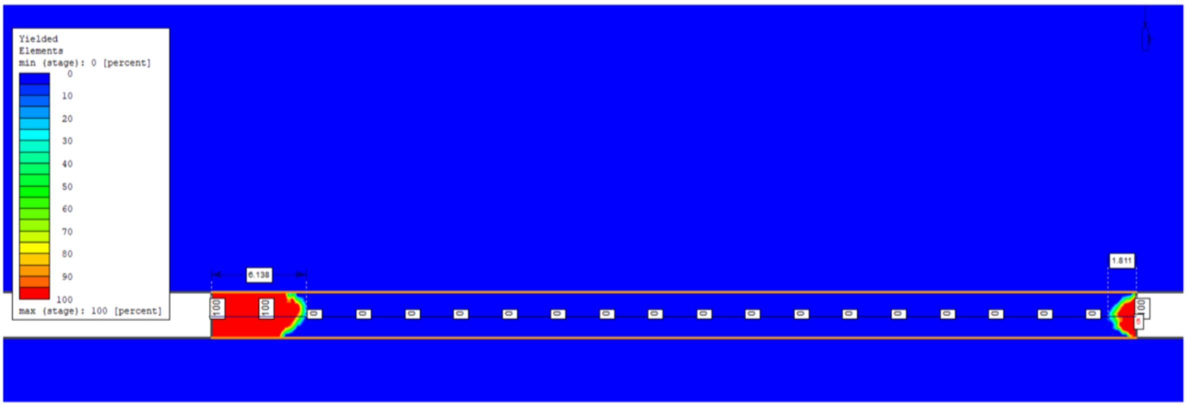

Fig. 6 Yield zone in a water barrier pillar at a water pressure of 0.1 MPa.

Figure 7 illustrates the pore pressure profile that is operating across the water barrier pillar.

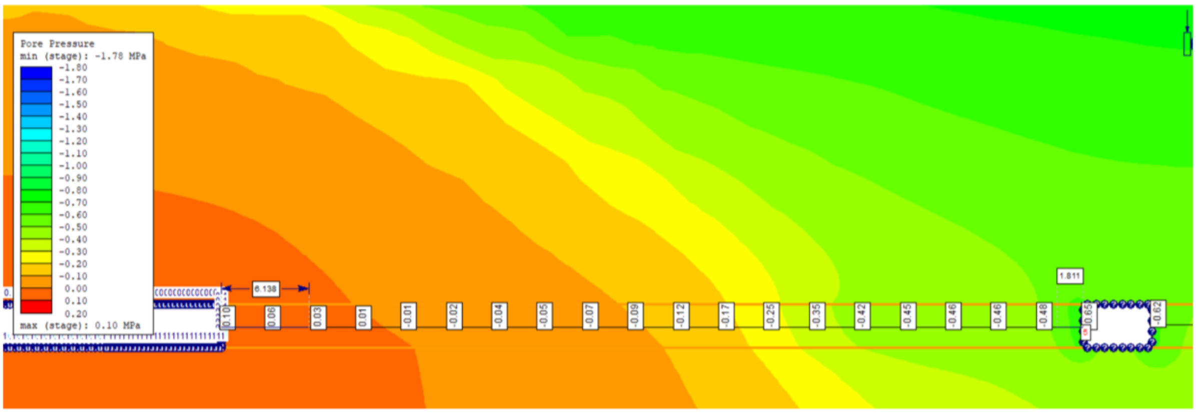

Fig. 7 Pore pressure across the water barrier pillar at a water pressure of 0.1 MPa.

The amount of water inside the goaf gradually grows, which causes a water pressure of 0.5 MPa to be exerted across the water barrier pillar. This ultimately leads to an even greater drop in the stability. At a greater water pressure of 0.5 MPa, the stability of the water barrier pillar decreases to 4.50, which indicates that the pillar becomes more unstable. This is because the pillar is subjected to a greater amount of pressure, which results in a wider yield zone compared to the elastic zone, as seen in Figure 8.

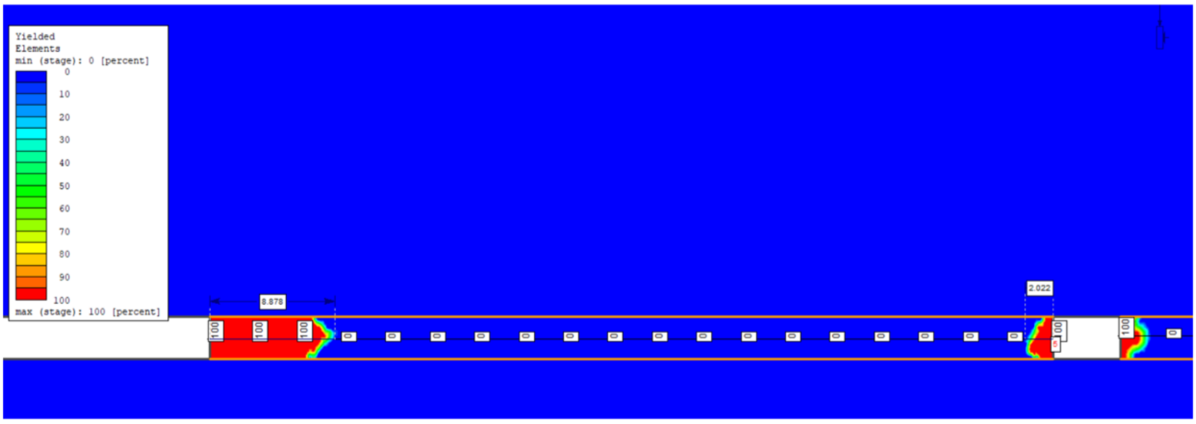

Fig. 8 Yield zone in a water barrier pillar at a water pressure of 0.5 MPa.

The stresses over the water barrier pillar in which a water pressure of 0.5 MPa acts can be seen in Fig. 9. Comparing it with Fig. 5, it can be seen that there is a high concentration of sigma 1 over the pillar near the goaf and leading to tensile failure and much wider yield zone.

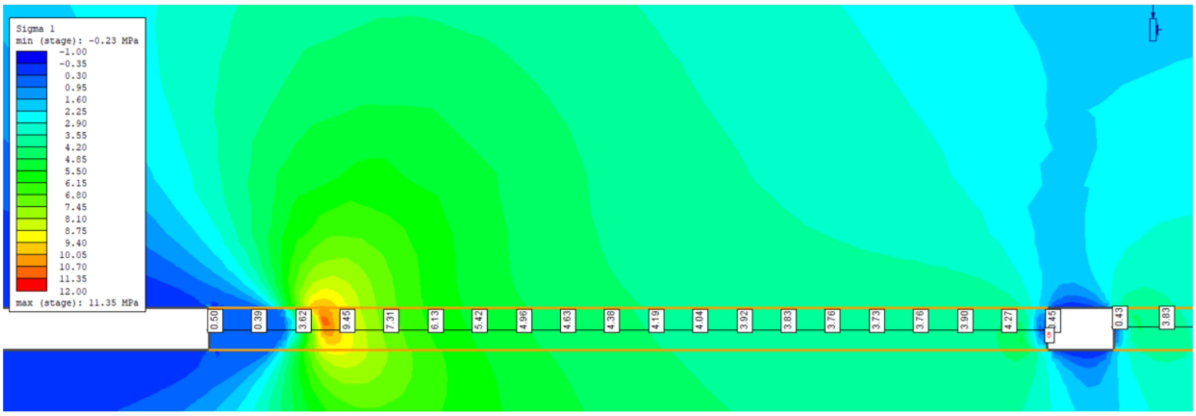

Fig. 9 The Stresses over the water barrier pillar under water pressure of 0.5 MPa.

Furthermore, with time, there will be a connection in the water barrier pillar, which leads to a higher flow of water across it till a steady state is achieved, resulting in the pillar's collapse. The rise in water across the barrier exerts higher water pressure, which tends to decrease the strength of the pillar and make it more prone to failure. From the above results, it can be understood that apart from mechanical properties, hydraulic properties also govern the parameters of the design of a water barrier pillar. In most countries, Empirical methods are used to design water barrier pillars, which is site-specific and lags behind in predicting the exact influence of the flow of water on pillar width. Therefore, there is a need for a rational method for the design of a water barrier pillar.

4 Conclusion

The research demonstrates that integrated mechanical and hydraulic characteristics are crucial for efficiently designing water barrier pillars in underground coal mines. Numerical investigation reveals two primary causes of water-induced pillar destabilisation: Changes in pore pressure due to hydraulic pressure influence modify effective stress states, possibly initiating plastic yield. Excess pore pressure caused by stress further alters the distribution of pore pressure.

The presence of water affects the integrity of pillars and results in hydraulic linkages between pillars and inundated workings. Elevated pore pressures result from increased water pressures, which cause a measurable decline in stability, shown by a fall in the elasticity ratio from 8.61 (dry circumstances) to 6.54 (under 0.1 MPa water pressure) and 4.50 (under 0.5 MPa water pressure) for a 60 m wide pillar.

The effect of water-on-water barrier pillars at varying depths and widths will provide an enhanced understanding of the mechanism of the water flow process. The development of comprehensive design standards integrating mechanical and hydraulic considerations incorporating joints and discontinuities will provide more realistic results.

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