Design of Protective Water Barrier Pillars for Enhanced Safety and Productivity in Underground Coal Mines

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Abstract

This paper highlights salient results of an R&D project recently completed by the authors with an aim to develop the know-how of hydro-mechanical coupled modelling of protective water barrier pillars and develop governing relations for assessment of their performance in a given geo-mining condition. It considers a cover depth of 100-350m and a pillar width of 15-120m to evaluate their mechanical stability in terms of the extent of zones of positive volumetric strain and seepage rate expressed in terms of GMP/km of pillar length for a range of extraction ratio, porosity, permeability, rock strength, and horizontal stress conditions. The limiting pillar width for piping failure has been defined along with the efficacy of 60m width pillars as mandated by regulatory provisions. The effects of cover depth and water head on the severity of water seepage have also been studied to highlight the requirements of controlled seepage and rational pillar widths along with the maximum allowable water head. The outcome of the study would be helpful in improving safety and mineral conservation in underground coal mines in Indian geo-mining conditions. It will also help the existing mines in organising their activities at a known level of risk against the danger of inundation due to the inadvertent failure of PWBP in underground workings.

1.0 Introduction

In the realm of underground coal mining, the safety and productivity of operations hinge on effective strategies to control water inrush and safeguard against inundation. A pivotal component of this defense mechanism is the deployment of protective water barrier pillars (PWBP), wherein intact coal blocks are strategically left unmined (Figure 1). The primary objective of PWBP is to establish a robust hydraulic barrier, providing isolation from waterlogged areas and fortifying active mine workings against the imminent danger of inundation. Despite the recognized significance of PWBP, a prevalent issue arises from inadequacies in the width of these protective pillars, thereby elevating the risk of inundation in underground coal mines.

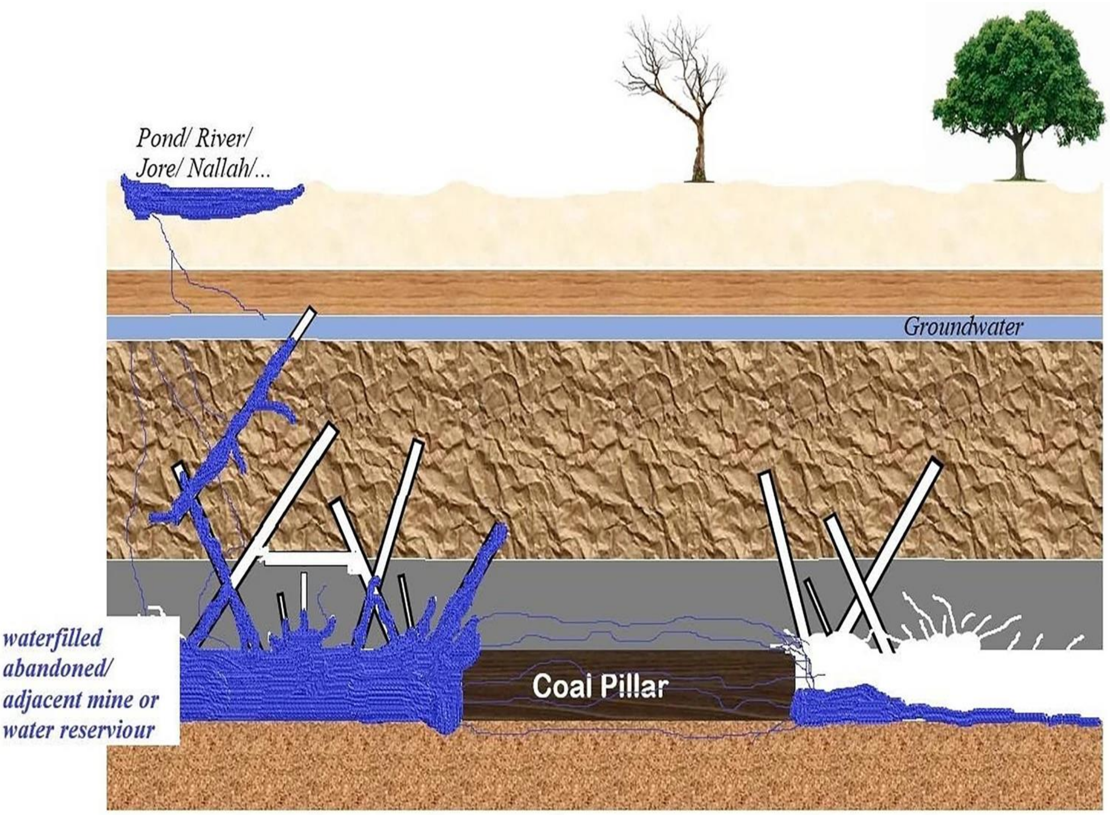

Fig. 1. Cross-sectional view of PWBP in a mine (Galav et. al, 2021)

The Bagdigi Colliery disaster underscores the perilous consequences of inadequate protective water barrier pillars (PWBP) in underground coal mines. With a reduced barrier pillar width, the mine faced a catastrophic inundation disaster, resulting in the loss of 29 lives. Despite regulatory guidelines, operational pressures often lead to compromises in safety standards. The regulation 150(3) of the Coal Mines Regulation 2017 mandates a 60-meter barrier, considered 'adequate' for protection, but deviations are common.

The research conducted by Job (1987) in British coal mines and Das et al. (2016) in Indian coal mines underscores the pivotal role of PWBP width in mitigating the threat of inundation from abandoned waterlogged workings. Based on the existing research gap, a hydro-mechanically coupled approach has been developed to understand the underlying coupled mechanism (Galav et. al, 2023). The statistical model has also been developed as a ready reckoner for the assessment of the hydro-mechanical stability of PWBP. This paper delves into the impact of the regulatory provision of 60 meters vis-à-vis critical width of piping failure on mine safety and productivity, aiming to propose optimal design approaches for protective water barrier pillars.

2.0 Past Experiences with PWBP

In the absence of scientific understanding, the inaccurate design of PWBP, has led to mine inundation disasters and the loss of life of several miners in India as well as across the globe (Galav et. al 2021). Some major inundation disasters of Indian mines are as follows:

(i) Loyabad Colliery, India - 16.01.1935- 11 Deaths
A poignant reminder of the consequences of neglecting protective measures, the Loyabad Colliery disaster occurred when a development gallery punctured into abandoned workings of the same mine. This incident underscores the imperative for robust design strategies to prevent inadvertent breaches and the potential for devastating outcomes.

(ii) Central Bhowrah Colliery, India - 20.02.1958 - 23 Deaths
Tragedy struck Central Bhowrah Colliery as the mine succumbed to inundation caused by a water inrush from abandoned workings of Sonardih Colliery. The loss of 23 lives emphasizes the critical role of effective barrier pillars in safeguarding against water-related disasters, underscoring the urgency for optimal design practices.

(iii) Silewara Colliery, India - 18.11.1975 - 10 Deaths
A stark illustration of the repercussions of inadequate barrier pillar design, the flooding at Silewara Colliery resulted from the failure of a thin barrier pillar, separating development working from waterlogged sections. The incident serves as a cautionary tale, highlighting the importance of comprehensive protective measures.

(iv) Chasnalla Colliery, India - 27.12.1975 - 375 Deaths
In a tragic turn of events at Chasnalla Colliery, a spark from equipment in a Degree-III gassy mine initiated a chain reaction leading to a catastrophic coal dust explosion. The explosion punctured the inter-mine barrier, connecting to a water reservoir, underscoring the intricate relationship between safety measures and the prevention of cascading disasters.

(v) Bagdigi Colliery, India - 02.02.2001 - 29 Deaths
The Bagdigi Colliery disaster stands as a somber testament to the consequences of an incompetent protective water barrier pillar. The reduced width of the pillar, ranging from 20-27 meters (some reports suggest 10 meter at failure), resulted in its failure under water pressure during routine blasting. This incident reinforces the critical need for optimal design to avert mine inundation disasters.

A recent survey conducted by the authors in 40 different underground coal mines showed that the barrier pillar width varied from 10–650 m at a cover depth of 18–300 m. Such pillar produced a seepage of almost insignificant to 4200 GPM/km when subjected to a water head of 10–206.7 m. More than 50% of the mines had a minimum barrier width less than the regulatory limit of 60 m. Some of these mines were facing problems of excessive water seepage, affecting their safety and productivity. A scientific design of such pillars could enable the mines to operate at a known level of risk apart from ensuring their long-term safety and productivity.

3.0 Numerical Modelling of PWBP

A hydro-mechanical coupled numerical modelling approach (Figure 2) was developed for assessing the performance of barrier pillars. It uses an explicit Finite Difference solution scheme of FLAC-2D software (ITASCA, 2011) along with representative strain softening behaviour, the effects of induced porosity and permeability on steady-state flow characteristics for field representative simulation of PWBP behaviour. Figure 3 shows the geometry and boundary condition assigned to the model.

A detailed parametric study was conducted for a cover depth of 100–350 m, pillar width of 15–120 m, and water head of 25–100% of cover depth to understand the mechanical and hydraulic performance of pillars in terms of the extent of zones of positive volumetric strain and seepage rate. The in-situ permeability varied from 0.25-100 mD for coal and 100-1000 mD for the immediate roof and floor.

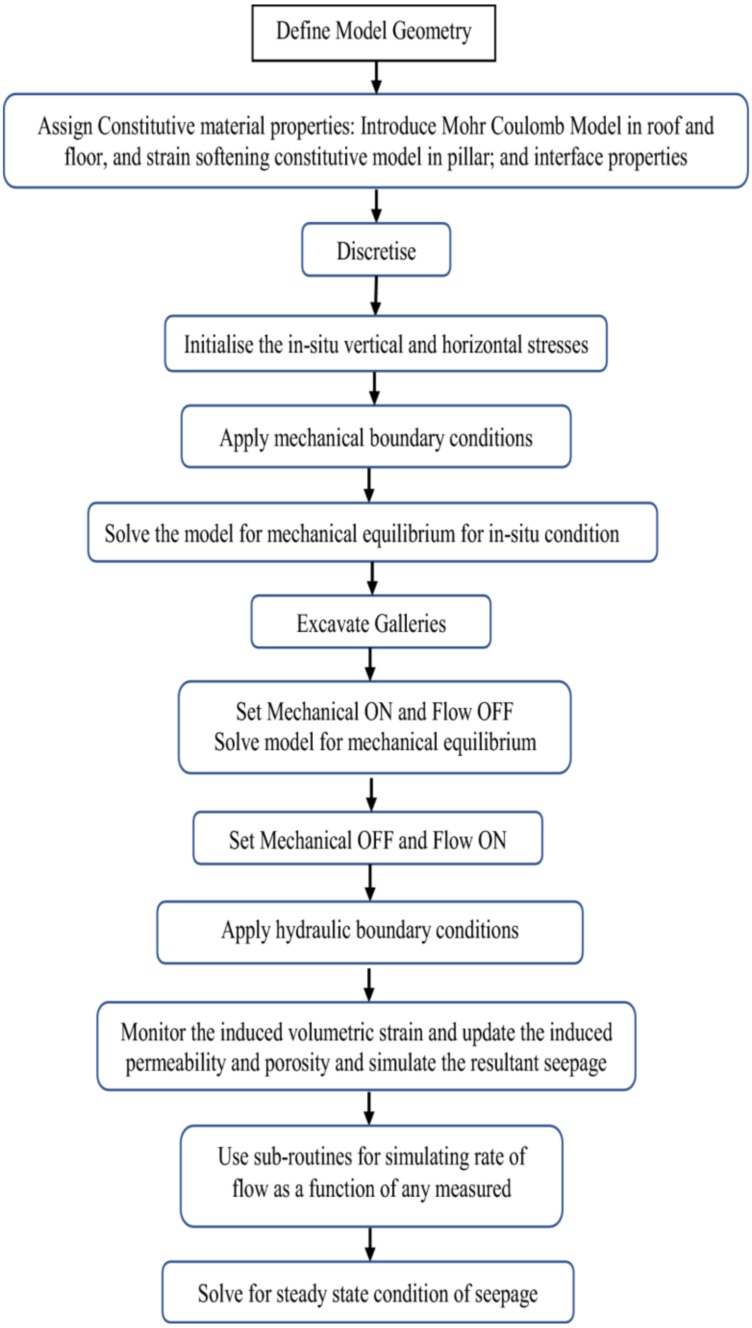

Fig. 2. Research Methodology (Galav et. al, 2023)

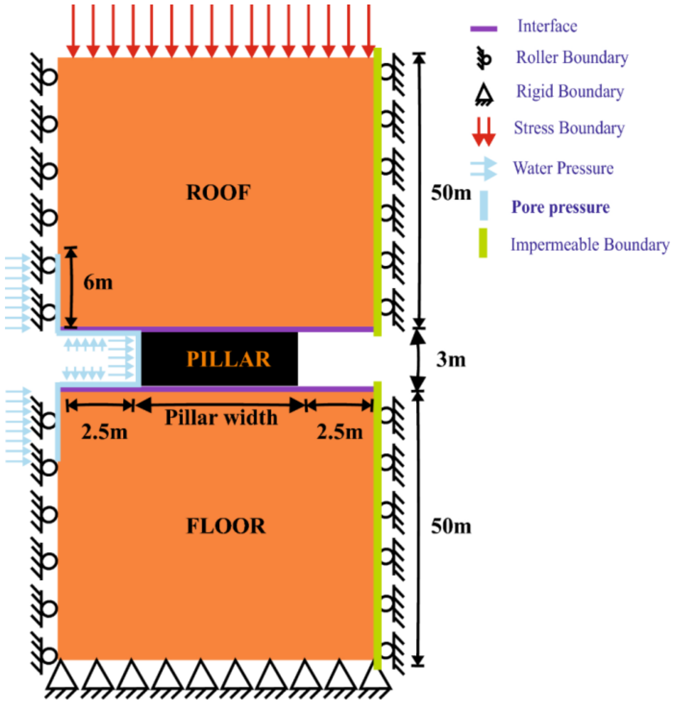

Fig. 3. Geometry and boundary conditions of numerical model (Galav et. al, 2023)

4.0 Results

The study to assess the effect of cover depth on ZOPVS of an undersized pillar of 30 m widths as compared to the baseline width of 60 m (Figure 4) showed that the extent of ZoPVS increased sharply for a reduced pillar size of 30 m compared to the nominal width of 60 m for increase in cover depth from 100-350 m. The ZoPVS for the reduced pillar width was 43.8% at the cover depth of 100 m, but it occupied the entire pillar at a depth of 350 m.

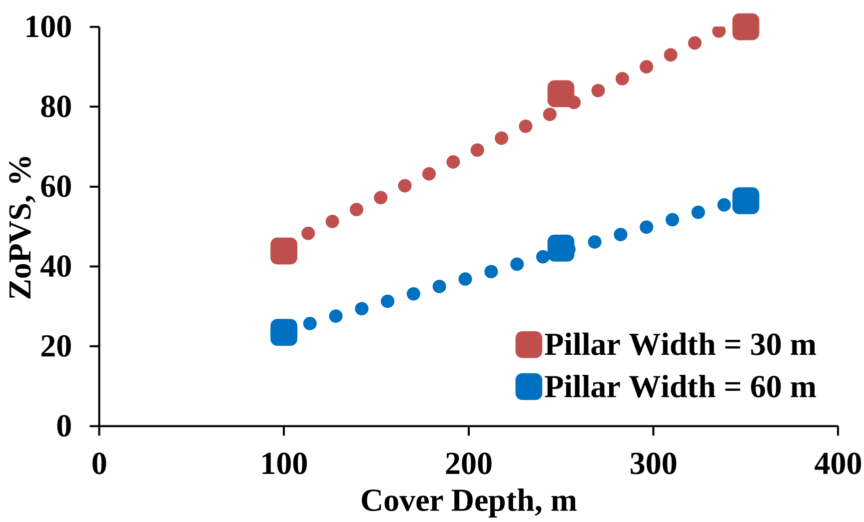

Fig. 4. ZoPVS vs cover depth plot for pillar width of 30 m and 60 m

Figure 5 shows the typical characteristic curve depicting the hydro-mechanical performance of PWBP at 100m depth. The result shows that for a given depth of cover and water head, the rate of water seepage through the pillar increases with the reduction in pillar width. A similar trend is also followed in terms of ZoPVS. The increase in the rate of seepage and the ZoPV becomes asymptotic as the pillar width reduces beyond a certain limit. The critical pillar width corresponding to a ZoPVS of 100 % marked its piping failure in a given geo-mining condition. The maximum allowable seepage of 5000 GPM per km marked the controlled seepage width for long-term sustainable performance.

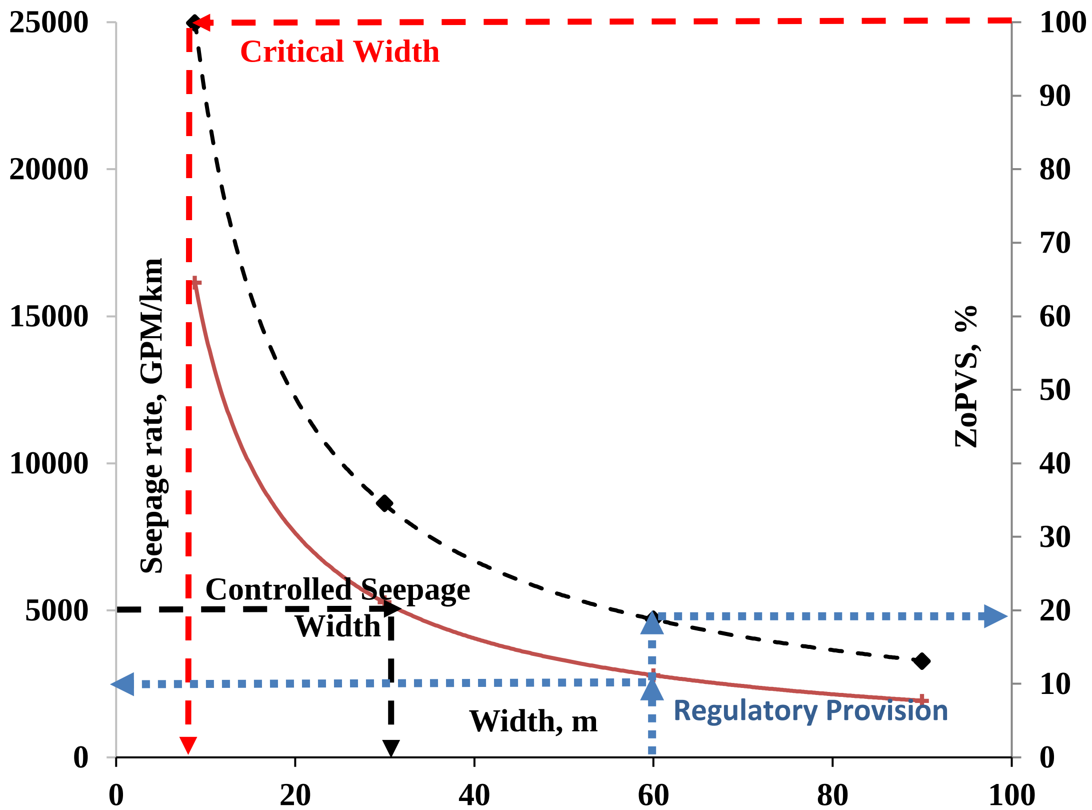

Fig. 5. Seepage and ZoPVS for varying pillar width in hard rock conditions at a water heads (WH) and cover depth (D) of 100 m

Figures 6-8 show the comparative hydraulic performance of the critical pillars width in the soft rock condition with respect to the regulation-mandated pillar width of 60m at varying water head of 25-100% at cover depth. The study revealed that although the critical pillar of 12m width at 100m cover depth and 31-34m width at 250-350m width produces seepage lower than the allowable limit for reduced water head of 25-40% of the cover depth. Such under-designed pillars are prone to experience an unstable hydro-mechanical behaviour in the worst water head of 100% of their cover depth, leading to inundation in the mine. On the other hand, the 60m wide pillar seems to be over-designed against the critical width of 12m for shallow depth of 100m as the ZoPVS and resultant seepage are significantly lower than the allowable limit even for 100% water head. However, such pillars are unable to contain the seepage for their acceptable performance at higher cover depth if the water head exceeds 50%. This highlights the need for rational design criteria for a long-term safety and sustainable performance in mines.

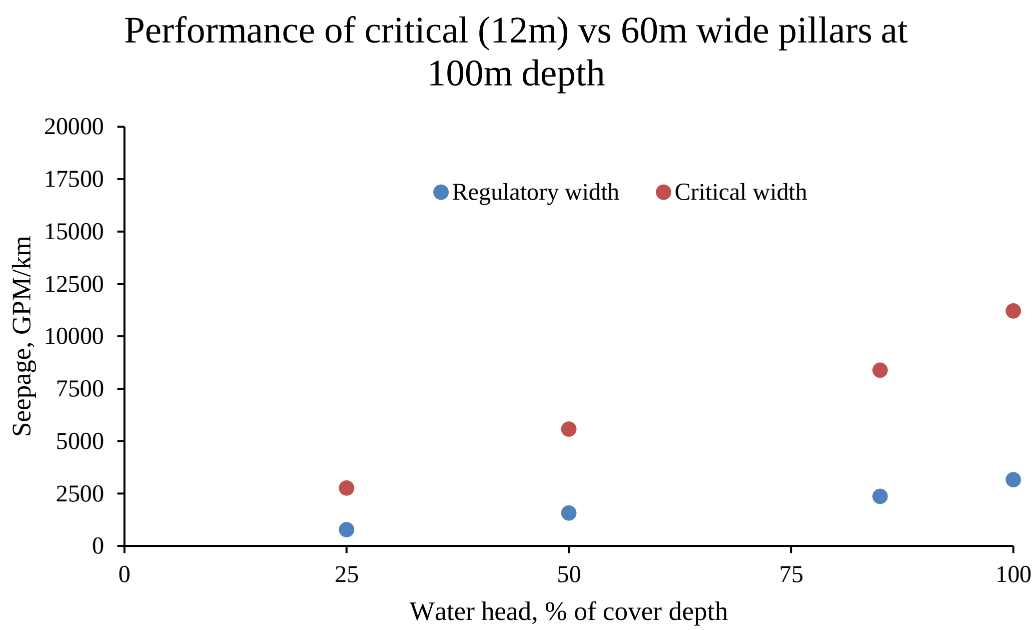

Fig. 6. Seepage through 12m and 60 m wide pillar at water head of 25-100% at 100m cover depth

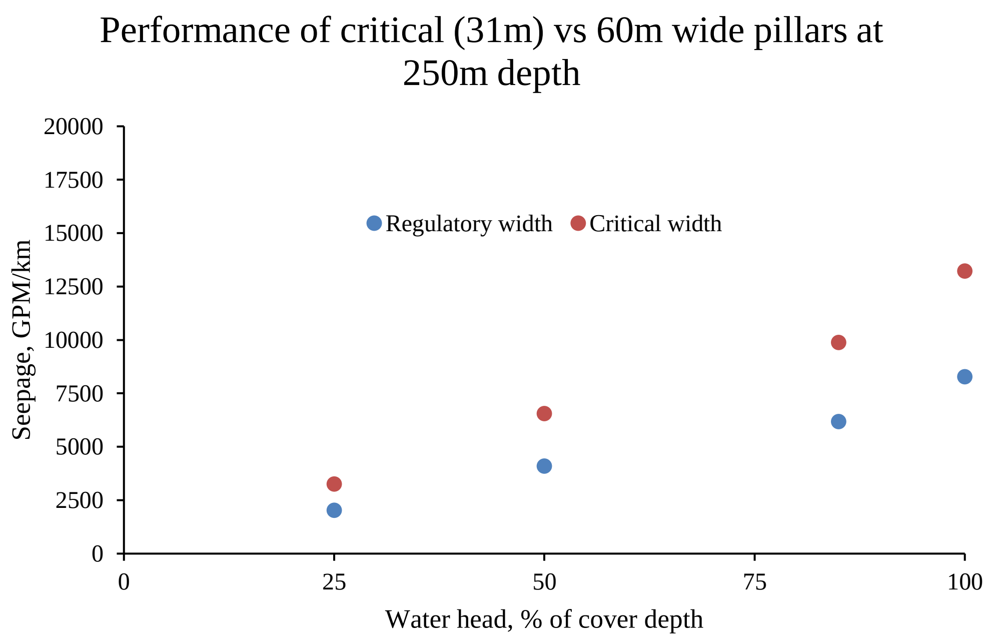

Fig. 7. Seepage through 31m and 60 m wide pillar at water head of 25-100% at 100m cover depth

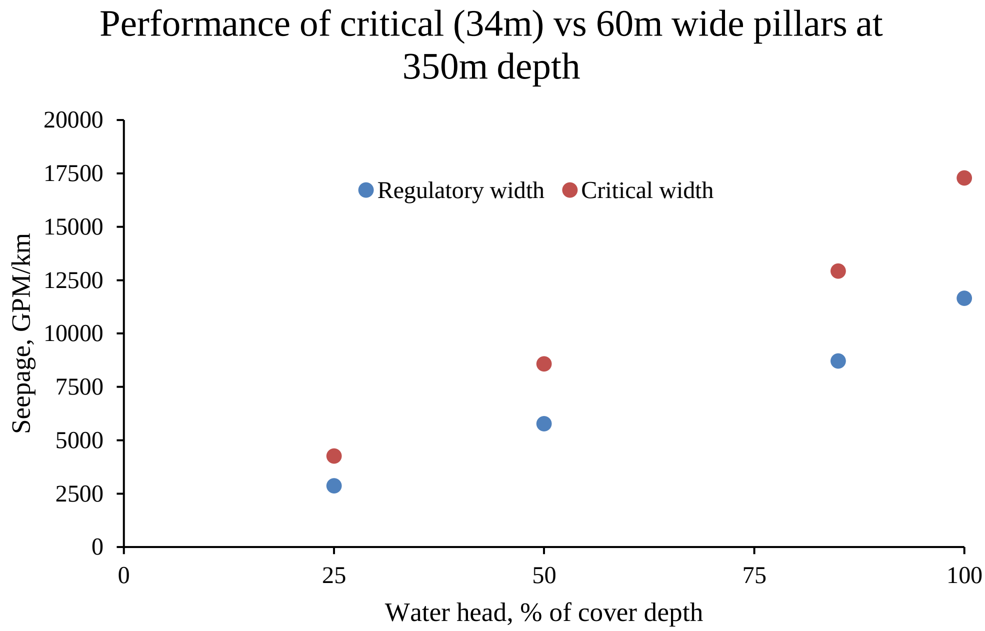

Fig. 8. Seepage through 34m and 60 m wide pillar at water head of 25-100% at 100m cover depth

The study pinpointed a critical width of 9-34 m depending on the strength of the coal, marking the onset of piping failure, corresponding to ZoPVS of 100% at cover depth of 100-350m. The pillar of 32.4 to 134.6m were identified for controlled seepage, aligning with a seepage rate of 5000 GPM/km for the worst water head of 100% of depth of 100-350m. However, the required pillar width reduced to 42-63m for lowered water head to 50% at 250-350m depth. These vital observations allowed delineation of allowable water heads for controlled seepage width as a viable alternative as such design would not only maintain hydro-mechanical stability but also lead to substantial resource savings, amounting to as much as 100%. This also highlighted the potential for optimizing pillar width to achieve a balance between stability and resource efficiency, particularly at shallow cover depth.

This study also allowed the development of statistical models for estimating the extent of ZoPVS (Equation 1) and the rate of water seepage (Equation 2) (Singh et al. 2023). It considers PWBP of 3m height and water-saturated influence zone of twice the pillar height in the roof as well as floor as the extent of the modelled zone of influence (MZoI).

$$ZoPVS = \frac{2.28\left(\frac{E_i}{E_c}\right)^{0.3} D^{2.39} e^{0.07}}{\sigma_{hc}^{3.88}\sigma_{cc}^{0.66} w^{0.82}} \qquad \ldots(1)$$

$$Q = \frac{0.48k\left(\frac{\sigma_c}{\sigma_t}\right)^{0.21}\left(\frac{E_i}{E_c}\right)^{0.03} D^{0.18} e^{0.02} H^{1.01}}{\sigma_h^{0.26} w^{0.90}} \qquad \ldots(2)$$

Where, Q= seepage through the pillar system, GPM/km; w = pillar width, m; e = extraction ratio; σ_{hc} = mean horizontal stress in coal seam, MPa; σ_h = mean weighted horizontal stress in the MZoI of roof_pillar_floor system, MPa; σ_{cc} = mean rock-mass compressive strength of coal, MPa; σ_c = mean rock-mass compressive strength of the MZoI, MPa; σ_t = mean rock mass tensile strength of the MZoI, MPa; E_i = Young's modulus of roof/floor, GPa; E_c = Young's modulus of coal, GPa; D = cover depth, m; H = water head, m, and k= weighted average permeability of the MZoI, mD

5. Conclusion

A hydro-mechanical coupled study was carried out to explore the relation between the ZoPVS representing the mechanical performance of the pillar, and the seepage rate signifying its hydraulic behaviour. The study indicated that the size of PWBP need not be the same for the avoidance of its piping failure in varying geo-mining conditions. The seepage rate through 60 m wide pillars did not change significantly irrespective of the coal strength. A pillar width of 12m was adequate to prevent its piping failure at the shallow cover depth of 100m. The critical width increased to 31-34 m at 250 - 350 m in the worst conditions. Defining the maximum allowable seepage for sustainable mining and a proactive control of the water head can further help in controlling the seepage in the mine. Such a strategy can enable a significant reduction in the mandatory limit of minimum pillar width, facilitating improved conservation of minerals, which otherwise gets permanently locked because of the excessively conservative design in the prevailing scenario. In cases where active control of the water head is not practicable, an optimal combination of rational pillar size and matching pumping infrastructure can be opted to deal with the requirement on a sustainable basis.

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