

8. Discussion

Protective Water Barrier Pillars (PWBP) are used to isolate active working areas from water-filled abandoned sections and control seepage rate and water inrush. When hydraulic pressure from water in the old workings surpasses a threshold, barrier pillars can fail, leading to potential inundation disasters. Existing data and practical experience support the idea that insufficient pillar width is a significant cause of these disasters. The Regulation 150(3) of the Coal Mines Regulation 2017 mandates a 60-meter buffer between active mining and water-filled areas, suggesting this width is "adequate." However, mines often operate with smaller pillars, relying on empirical experience and ignoring factors like cover depth, water head, rock properties, and geological discontinuities.

A random survey of 40 underground coal mines in various coalfields in India found that over 50% of the mines did not meet the minimum statutory requirement. While PWBP of 50-650 meter width at a cover depth of 18-164 meters experienced negligible seepage rate at a water head equal to their cover depth, PWBP of 13.5-180 meters width at cover depths of 72-300 meters produced seepage rate of 6.3 to $63 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (100 to 1000 GPM/km) at water heads of 24-207 meters. PWBP of 25-50 meters widths at cover depths of 90-175 meters and water heads of 13-141 meters resulted in seepage rate of $126-158 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (2000-2500 GPM/km) and PWBP of 20-120 meters widths at cover depths of 80-167 meters and water heads of 15-80 meters produced water seepage rates of $189-265 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (3000-4200 GPM/km). A barrier pillar of 200 meters at a cover depth of 18-91 meters and another of 650 meters width at a cover depth of 78-164 meters experienced no seepage. These findings highlighted a wide variation in the hydraulic performance of PWBP in Indian coal

mines, including instances where seepage rate was effectively controlled and cases where it created practical difficulty. Such data underscores the need for standardized guidelines and practices in the management of protective water barrier pillars to ensure long-term safety and productivity and minimize the risk of mine inundation.

A large amount of coal is sacrificed in PWBP. On the other hand, the barrier pillar of 10-20m width at 240m depth at Bagdigi mine in Jharia coalfield suffered a breach and failed to perform its designed function, causing a considerable loss. Similar disasters occurred at Silewara Colliery, Chasnallah Colliery, Central Saunda Colliery in India, Montagu Colliery and Audley Colliery in the UK, and North Virginia Mine, Spring Mountain Mine and Lytle Mine in the USA. Hence, the design of PWBP needs to be rationalised based on scientific considerations, especially the safety and techno-economics of the structure. The issue is becoming critically important with the increasing depth of working. Hence, a reliable assessment of the integrity of the existing barrier pillars and the rational dimension of new barriers under the increasing depth of the mine becomes most significant.

Prevailing Understanding

Among the prevailing approaches, the depth of working is a commonly used parameter to determine the size of the protective barrier pillar. Typical estimates suggest pillar widths of 25-30 meters at a cover depth of 100 meters and 50 meters at a cover depth of 350 meters. However, these approaches provide only a basic design and do not project the hydraulic performance of the pillar under varying water head conditions. The stability of protective barrier pillars is strongly influenced by the pillar width, the nature of the immediate roof and floor, and changes in confining stress.

Long-term exposure to water can weaken the strength and deformability of coal measure rocks, potentially leading to mechanical failure. Moreover, excessive water seepage rate can result in piping failure, where water erodes minerals and joint-filling materials, creating voids that weaken pillar support. This may lead to pillar collapse, roof collapse, and inundation in the mine. A protective water barrier pillar can be considered to have failed if the seepage rate is high enough to cause piping failure or exceeds the maximum allowable limit, posing a risk of unmanageable inundation.

The porosity and permeability of coal seams and associated rocks are influenced by deformation in the rock mass. In-situ porosity and permeability are low but change significantly with rock disturbance and strain. Induced permeability in the rock is fracture-driven, decreasing as rock fractures close and vice versa. However, it increases with plastic softening and residual loading-induced deformation. These factors affect the behavior of protective water barrier pillars in coal mines.

Simulation of Strain Softening Behaviour

A field representative constitutive behavior of coal pillars under mechanical loading was established to simulate the hydro-mechanical coupled phenomenon. Strain-softening parameters were determined by replicating the load-deformation behavior observed in laboratory tests of coal specimens from six Indian coal seams with width-to-height (w/h) ratios ranging from 0.5 to 13.5. These coal specimens had varying unconfined compressive strengths (UCS) between 19.5 and 47.5 MPa, Young's modulus from 1.82 to 4.0 GPa, and peak cohesion and friction angle ranging from 3.95 to 10.34 MPa and 35-51°, respectively.

A parametric study involved varying zone sizes from 0.5 mm × 0.5 mm to 2 mm × 2 mm, cohesion drop (CD) rates up to 250 MPa/plastic shear strain, residual cohesion (CR) values up to 100% of peak cohesion, friction angle reduction (FR) rates ranging from 100 to 500 degrees/plastic shear strain, and residual friction (FR) values up to 90% of peak friction angle. This was done to find the most appropriate behavior to match laboratory test observations for coal specimens with w/h ratios from 0.5 to 13.5. The dilation angle was updated using the Walton and Diederich (2015) model. If the desired stress-strain behavior was not achieved with the initial values, adjustments were made to CD, CR, FD, and FR in the model till an acceptable trend was obtained.

In the first stage, the models were tested with different cohesion drop rates and residual values. The friction angle drop rate and residual values were adjusted in the subsequent step, creating various combinations of CD, CR, FD, and FR to match the stress vs. strain behavior with laboratory observations. The best-fit findings were used to develop statistical models (Equations 4.1–4.4) for estimating cohesion and friction drop and their residual values based on factors like compressive strength, friction angle, elastic modulus, w/h ratio, and zone size.

The study found that coal pillars with a w/h ratio less than 4.5 experienced greater volumetric expansion compared to compaction when subjected to loading, resulting in a reversal of strain when not significantly confined. However, larger pillars did not exhibit this reversal and continued to exhibit positive volumetric strain as axial strain increased beyond the peak strength.

Formulation of hydro-mechanical Coupled Model for PWBP

Several parameters and methodologies were employed to simulate the hydro-mechanical behavior of the PWBP. The numerical model included a 50-meter-thick roof and floor strata, a 3-meter pillar height, and a 5-meter gallery width at cover depths ranging from 100 to 350 meters. The influence zone for fluid flow through the immediate roof and floor was considered to extend up to twice the pillar height. Element size within the model was set at 0.5 meters in both horizontal and vertical directions. Interface elements with suitable stiffness and strength properties were introduced at the contact plane of the coal seam with the immediate roof and floor to simulate slippage, enhancing the realistic modeling of confinement effects. The model incorporated the variation in the dilation angle as a function of plastic shear strain, following the approach suggested by Walton and Diederich (2015). Porosity and permeability in the Modeled Zone of Interest (MZoI) were also updated based on induced volumetric strain, following relations recommended by ITASCA (2011) and Zhu et al. (2015). The simulation used Biot's theory for porous media, accounting for Darcy flow. It assessed the mechanical and hydraulic parameter changes and their coupled interactions by using a FISH function 'QRATIO.FIS' to monitor the equilibrium condition for steady-state analysis, ensuring that the total inflow and outflow converged to a common value, and the qratio approached zero. Mechanical stability of the PWBP was assessed in terms of positive volumetric strain zones, redistribution of induced vertical stress, and the rate of water seepage for varying pillar widths to understand the phenomena of piping failure and controlled seepage rate.

Parametric Study

A comprehensive analysis was conducted to investigate the Zone of Positive Volumetric Strain (ZoPVS) and the rate of seepage through the PWBP across a wide range of parameters. It encompassed variations in strength, pillar width, permeability, water head, and cover depth, covering various flow conditions. For each flow regime, the study incorporated the variation in working depth from 100-350 m, pillar width from 15-120 m, extraction percentage from 10-44, water head from 25–100 % of cover depth, and three levels of rock mass strength classified in terms of soft, medium and hard. The rock mass compressive strength varied from 2.04 to 6.32 MPa for the soft to the hard category of coal and 4.01 to 20.92 MPa for the rock. The tensile strength ranged from 0.04 to 0.71 MPa for the coal seam and 0.39 – 2.39 MPa for the rock.

With the increase in cover depth from 100-350m, the pillar of 60m width showed a rise in ZoPVS from 23.5 – 56.4% in the pillar. The increase in the extent of failure caused a reduction in the effective width to resist water seepage rate. The ZoPVS increased more sharply from 43.8% at 100m depth to 100% at 350m depth in the pillar of 30m width. A similar trend was observed in terms of the water seepage rate as well, wherein the seepage rate of $0.5 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (7.6 GPM/km) was observed condition at 100 m cover depth, which increased to $1.8 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (29.2 GPM/km) at a cover depth of 350m in the ‘pillar only’ condition. For a 30 m wide barrier pillar, the seepage rate of $1.2 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (19.1 GPM/km) at 100 m cover depth increased to $9.3 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (147.6 GPM/km) at 350m cover depth. These findings agreed with Moeb (1989), underlining the requirement for larger pillar width at higher cover depth.

The study of the effect of pillar width showed ZoPVS of 25 % for the 120m wide pillar at 250m depth which increased to 100% in the 30 m wide pillar. The core zone characterised

by non-positive volumetric strain reduced with a reduction in PWBP width. The seepage rate also increased following a similar asymptotic trend as observed for the ZoPVS with the reduction in pillar width. Smaller pillars developed positive volumetric strain up to 100% of their extent and were unable to provide a meaningful hydraulic resistance against the imposed water head, creating a sharp increase in the seepage rate. Such behaviour of the pillar indicated its piping failure as conceptualized by Kesseru (1978).

The effect of in-situ permeability was studied for coal pillar varying from 0.3 to 100 mD. The seepage rate increased linearly with the permeability. Although the state of stress-dependent volumetric strain induced in the pillar of given remained the same for a given cover depth, the induced permeability was high for the high in-situ permeability of the rock. Consequently, greater seepage rate was observed in pillars with higher in-situ permeability. The peak vertical and horizontal induced stresses increased with the decrease in pillar width. The extent of the intact zone decreased from 75 % to almost zero, while the yield zone increased from 25 to 100 %. For the critical width of 30 m with no intact zone remaining in the pillar, the extent of induced positive volumetric strain zones increased sharply, causing the pillar to become unstable. This was also characterized by a sharp change in induced permeability in the yield zone having positive volumetric strain. The induced vertical stress in the core was lower w.r.t. the edges of the pillar of 120-60 m width. However, as the pillar width was reduced to 30 m, the peak-induced stress shifted from the edges to the core. The edges of the pillar were almost distressed irrespective of the pillar size, while their core held a higher confining stress. However, the core size got reduced with the reduction in the pillar width.

For pillar width higher than its critical value, the induced permeability was higher at the edges only, and the pillar had a significant core in intact condition. However, with a reduction in pillar size to its critical limit, the induced permeability increased significantly, covering the whole width of the pillar, and the intact zone in the pillar reduced to a negligible value. The pillar received the peak vertical stress in the centre during such condition.

The profile of induced vertical and horizontal stress was almost symmetrical in the mechanical loading condition. However, with increasing water head, the effective stress was higher in the reservoir side as compared to the active working side. The profile of induced permeability confirmed a significant effect of the confinement and the extent of ZOPVS with the canging pillar width that dictated the flow pattern through a pillar. However, the seepage rate through pillars formed of hard rock was lower while the pillars formed of soft rock suffered the maximum seepage rate.

The least seepage rate of water was noted for the ‘pillar only’ condition while the maximum seepage rate was observed through the pillar system. The ‘floor only’ condition produced a marginally higher seepage rate as compared to the roof only condition. The seepage rate through the pillar was $115 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (1827.0 GPM/km) in comparison to the marginal value of $1.5 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (24.6 GMP/km) through the pillar width of 60m subjected to water head of 125 m in the medium strength rock condition.

The overall findings of the study confirmed that large cover depth transfer a higher load on a pillar for a given extraction percentage. Under such condition, under-designed barrier pillars may develop a significantly large ZoPVS, which is prone to mechanical as well as hydraulic failure in the worst conditions. The decreased width of intact zone in the pillar compromised its overall effectiveness to restrict the water seepage, causing increase in the

rate of seepage. The higher permeability of rock mass worsened the situation further by facilitating the seepage rate. Higher rock mass strength provided only a marginal support to the stability of the PWBP as the weakening caused by the water absorption reduced its effective strength drastically in the water-saturated condition. Among the potential flow regimes, the pillar system exhibited the least favorable water seepage rate.

Governing Rule and Design Criteria

The criteria for delineation of piping failure and controlled seepage rate were developed considering the characteristic ZoPVS, and seepage rate profiles for pillar system, and the seepage rate severity classification proposed for the Indian coal mines. The governing equation for ZoPVS considered the modulus ratio of the immediate roof/floor and coal, cover depth, average insitu horizontal stress, uni-axial compressive strength and pillar width to quantify the mechanical damage of a pillar and its effectiveness in controlling the seepage rate of water. The relation for the rate of water seepage considered the weighted insitu permeability of the roof, pillar and floor in the MZOI, the strength and modulus ratio of the immediate roof/floor and coal, cover depth, water head and the weighted average insitu horizontal stress to estimate the hydraulic performance of the pillar system. These findings agreed well with Moebs and sames (1989) with regard to the increasing cover depth and the water head and Shen et al. (2012), LaMoreaux et al. (2014) and Liu et al. (2021) concerning the effect of high in-situ horizontal stress on the damaged zone and seepage rate across the barrier under high water heads.

The Seepage rate severity classification considered the minimum seepage rate and the pumping standby time of 10 hours daily for knee depth ponding upto two pillar distance from the PWBP within the time period of 1 day, 1-3 days and more than 3 days as practiced in the

mines to classify the severity of seepage rate in low, moderate and high categories. Accordingly, the maximum allowable seepage rate of $315 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (5000 GPM/km) was reckoned for controlled seepage rate and avoidance of inundation in the mine. The design limits for different severity classes match well with the field experience.

The most substantial increase in the rate of seepage change was observed when the pillars reached 100% of the Zone of Permeable Veneer Surrounding Pillars (ZoPVS), indicating the initiation of their unstable hydraulic behavior under all tested conditions. The rapid escalation in water seepage rate at this point signifies a potential piping failure, which could lead to unintended flooding in the mine. Accordingly, the maximum pillar width for ZoPVS of 100% was considered as the critical width in this dissertation. The critical pillar width was noted as 8.8 m for 100 m cover depth, 21.9 m for 250 m and 24.2 m for 350 m depth. The field experience of Bagdigi mine in Jharia Coalfields at cover depth of 240 m supported these findings.

The results of water seepage rate through the regulation mandated pillar width of 60 m vis-à-vis the critical pillar width subjected to water head of 25–100% of the cover depth of 100–350 m in soft and hard strata conditions indicated that the size of PWBP need not be the same for the avoidance of its piping failure, irrespective of the cover depth. The seepage rate remained relatively constant for a pillar width of 60 meters across a range of rock strength.

The study of water seepage rate through the CMR recommended width of 60 m for different cover depths and variable water head showed its reducing trend with a reduction in a water head from 100-25% at a given cover depth. At a cover depth of 100 meters, the seepage rate decreased from 199 to $49 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (3152 to 778 GPM/km) in the soft rock condition and from 197 to $49 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (3125 to 771 GPM/km) in the hard rock condition. With

an increased cover depth of 250 meters, the seepage rate decreased from 517 to 128×10^{-3} $\text{m}^3/\text{s}/\text{km}$ (8207 to 2024 GPM/km) in the hard rock and from 522 to 129×10^{-3} $\text{m}^3/\text{s}/\text{km}$ (8279 to 2042 GPM/km) in the soft rock condition. It decreased from 728 to 179×10^{-3} $\text{m}^3/\text{s}/\text{km}$ (11548 to 2848 GPM/km) in the hard and 734 to 181×10^{-3} $\text{m}^3/\text{s}/\text{km}$ (11650 to 2873 GPM/km) in the soft rock condition for a similar reduction in water head at the cover depth of 350 m. The decreasing trend of water seepage rate was also confirmed for the critical pillar widths. These results indicated that proactive control of the maximum water head could be helpful in controlling the seepage rate through a barrier pillar in the mine.

The seepage rate produced by the 60 m wide pillar was about 37 % less as compared to the maximum allowable seepage rate for the worst condition of water head at 100 m cover depth. On the other hand, the water seepage rate through such pillar was above the permissible seepage rate limit for water head of 75 % and above at 250 m cover depth and 50 % and above at 350 m cover depth. The study also indicated that while the regulation recommended width is oversized by 2.48 – 6.81 times to avoid piping failure at the cover depth of 100-350m, it is not adequate to limit the maximum seepage rate within the permissible limit in moderate and deep mine workings. The water head needed regulation of 43-60% of the cover depth to fulfil the requirement of controlled water seepage rate.

The study for the desired width of the PWBP for a controlled water seepage rate (maximum allowable seepage rate of 315×10^{-3} $\text{m}^3/\text{s}/\text{km}$ (5000 GPM/km)) in soft and hard rock conditions when subjected to a water head of 25–100 % at the cover depth varying from 100–350 m indicated that the PWBP width needed to be increased for a controlled seepage rate under increasing cover depth and water head. The required width of PWBP varied from 2.6-5.5 times the critical width for the worst possible water head for this range of cover depth.

These estimates explained the inadequacy of 49 m wide PWBP at cover depth and water head of 209 m at Ninga mine in Raniganj Coalfields, which was hydro mechanically stable to meet its primary requirement but yielded 50 % more seepage rate as compared to the permissible limit. A PWBP of 75m width could have been adequate to provide the controlled water seepage rate in such a condition.

The study reveals that the pillar size required to achieve the maximum allowable seepage rate shows minimal variation with rock strength. However, the critical width of the pillar is notably influenced by the rock's strength. Specifically, at a depth of 100 meters, the critical width is 8.8 meters for hard rock and 12.4 meters for soft rock conditions. This critical width increases to 24.2 meters for hard rock and 34 meters for soft rock conditions when the depth is extended to 350 meters. The PWBP should not only provide safety against the danger of inundation due to its inadvertent failure but also contribute for effective control of water seepage rate within the maximum permissible limit for avoidance of mine inundation. As a result, the rational width of the PWBP is determined, corresponding to ZoPVS of 50%. The results consistently confirmed a controlled seepage rate of water along with the physical stability of the pillar for its long term acceptable performance.

Model Validation

The approach for assessment of hydro-mechanical performance and design of rational PWBP were validated for two case studies pertaining to Satgram Incline, and Lower Kenda coal mines in Raniganj Coalfield. The minimum width of PWBP was 60m at Satgram Incline mine and 30 m at Lower Kenda mine. The cover depth of the barrier was 84.5 and 134.5 m. The study confirmed moderately severe seepage rate at Satgram Incline mine and severe seepage rate at Lower Kenda mine. These projections are in agreement with the field

observation. The ZoPVS of 15.28-37.86 % for these pillars confirmed their mechanical stability. The PWBP at Satgram Incline mine was oversized by 287 % wrt the rational width of 15.5 m but it required controlling the water head to 59.5 m. The ZoPVS for the 60 m wide barrier was 15.03 %, while the total seepage rate through the pillar system was $117.6 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (1866.2 GPM/km) for the condition prevailing in the mine. The numerical modelling results corroborated sufficiently with the estimated ZoPVS of 15.28 % and the total seepage rate of $130 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (2063 GPM/km). The critical width corresponding to 100 % of ZoPVS was only 7m, while the controlled seepage rate width for the steady state flow of $315 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (5000 GPM/km) was 22.8m. The calculated rational width was 15.5 meters, whereas the existing width in the field is 60 meters. These findings collectively indicate that the current pillar design is overly conservative and oversized for the current conditions. It would be necessary to manage and limit the maximum water head to 59.5 meters to operate the mine with controlled seepage rate at the rational width of the PWBP. The depillaring working in seam V of Lower Kenda mine shares its boundary with the waterlogged Haripur mine with the PWBP of 30m width at cover depth of 134.5 m. The pumping rate of the mine is $151.2 \times 10^{-3} \text{ m}^3/\text{s}$ (2400 GPM) in the normal season, which increases to $226.8 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (3600 GPM) during the rainy season. The PWBP was producing more than the permissible seepage rate owing to unregulated water head in the abandoned mine working causing its periodical flooding and frequent mine closure. It needed enhancing pumping capacity by about $38 \times 10^{-3} \text{ m}^3/\text{s}$ (600 GPM) to avoid the mine flooding during the monsoon period. These modelling based results matched well with the field observed severity of seepage rate and visual observation pertaining to flow characteristics and weathering of infill material from the pillar-roof interface in the mine.

The modelling results showed ZoPVS of 33.61 %, while the total seepage rate was $315 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (5000 GPM/km) at the water head and cover depth of 134.5 m as prevailing in the field. These results corroborated well with the estimated ZoPVS of 37.86 % and the total seepage rate through pillar system of $338.3 \times 10^{-3} \text{ m}^3/\text{s}/\text{km}$ (5370 GPM/km). The ZoPVS observed in this context was significantly lower than its critical value, suggesting stable behavior. The high severity of seepage rate is responsible for the periodic flooding incidents in the mine. The critical, controlled seepage rate, and rational pillar widths were determined to be 9.8, 32.4, and 21.8 meters, respectively, for this mine. The implementation of the rational pillar width would necessitate control of the maximum water head to 94 meters.