7. Model Validation

7.1 General

The numerical modelling approach for assessment of hydro-mechanical performance of PWBP and the design criteria for rational pillar width was validated for two case studies pertaining to Satgram Incline, and Lower Kenda coal mines in Raniganj Coalfield. Figure 7.1 shows the location of these mines.

Figure 7.1. Geographical location of mines under study

7.2 Satgram Incline Mine

The Satgram Incline mine is working the Dishergarh (R-IV) seam at a cover depth of 65-130 m. The coal seam is completely developed, and depillaring is under progress at present. The leasehold area of the mine is 2300000 m^2 with a total mineable area of 703800 m^2. The mine was developed with a pillar size of 30 × 30 m (center-center) and a gallery width of 4.5 m. The extraction height is 2 m. The mine shares its boundary with Jamuria A-B Pit Colliery, which was abandoned about 30 years before and is completely waterlogged at present (Figure 7.2.) The borehole section placed beside the joint mine plan shows that sandstone forms the dominant rock type in the roof and floor of the coal seam. The immediate roof of the coal seam is formed of shale and intercalation rocks. The minimum width of the inter-mine barrier is 60 m, which extends along length to a distance of 800 m. The maximum cover depth of the PWBP is 84.5 m.

In the numerical model, the pillar of 2 m height and 4 m high zone of influence (twice the pillar height) was considered in the roof and the floor. The immediate roof was mostly composed of carbonaceous shale laminations, whereas the floor was of fine-grained sandstone.

The numerical model formulation considered representative interface elements, model discretisation, in-situ stresses, rock mass strength, mechanical and hydraulic loading conditions, and constitutive behaviour for pillar and roof/floor rock materials, as per the standard modelling scheme, explained in Section 3, Chapter 3. Table 7.1 shows the stratigraphy and rock mass properties considered in the numerical model.

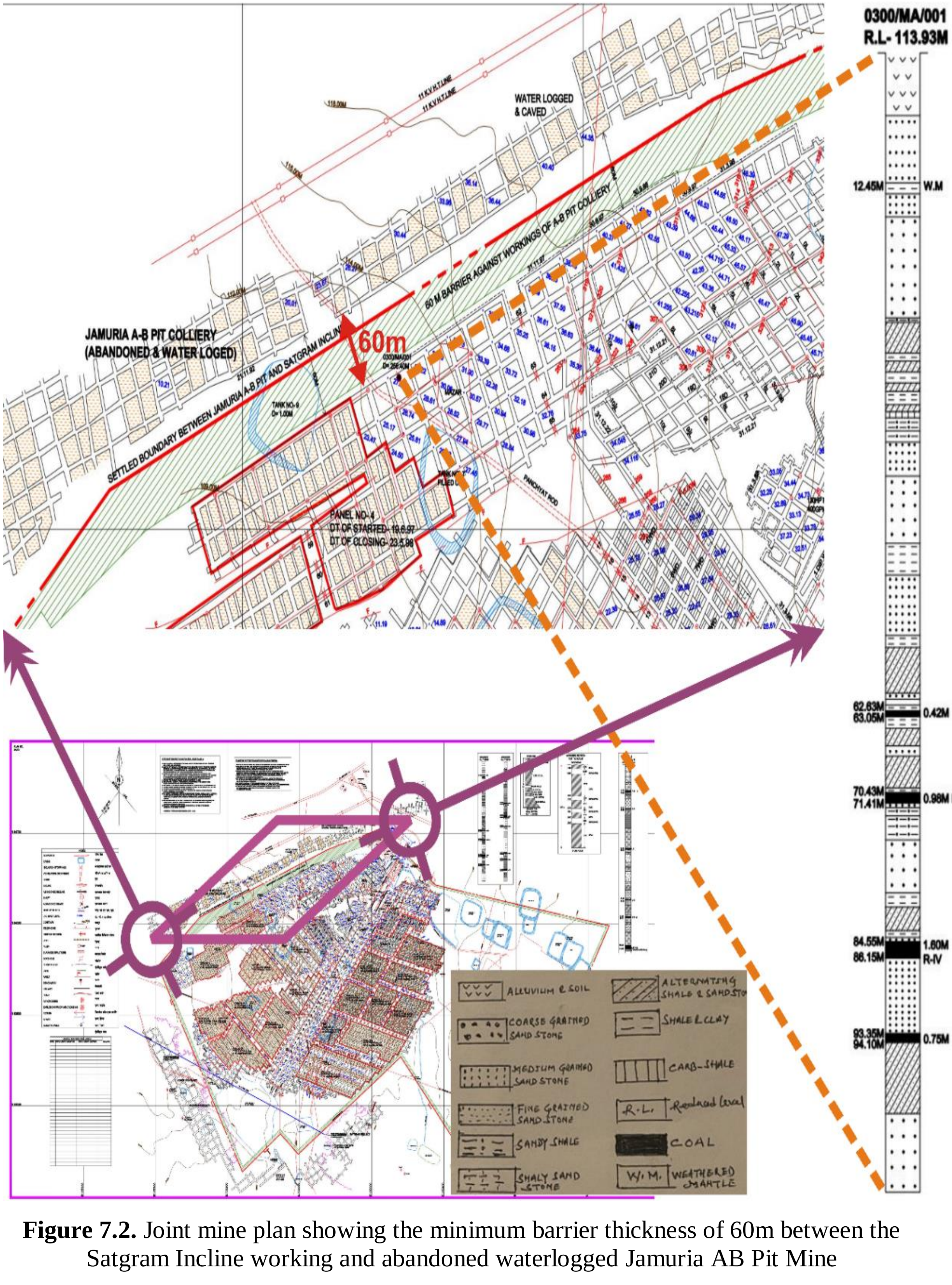


Figure 7.2. Joint mine plan showing the minimum barrier thickness of 60m between the Satgram Incline working and abandoned waterlogged Jamuria AB Pit Mine

Table 7.1. Rock mass data for the numerical modelling of Satgram Incline mine working

Structure	Thickness, m	Density, kg/m^3	Shear mod., GPa	Bulk mod., GPa	Tensile strength, MPa	Cohesion, MPa	Friction angle, °	Dilation angle, °
Alluvium & Soil	6	1775	0.27	0.45	0.06	0.10	40	5
Intercalation	56.5	2335	4.86	8.10	1.82	3.81	40	5
Coal	0.5	1380	0.74	2.22	0.60	1.91	25	2
Intercalation	7.5	2334	5.37	8.94	1.79	3.56	40	5
Coal	1	1380	0.74	2.22	0.60	1.91	25	2
Shale, Clay	4	2341	4.68	7.80	1.17	2.02	40	5
Medium Grained Sandstone	5.5	2293	4.07	6.79	1.48	3.47	40	5
Intercalation	3.5	2334	5.37	8.94	1.79	3.56	40	5
Coal	2	1380	0.74	2.22	0.60	1.91	25	2
Fine Grained Sandstone	7	2373	5.35	8.92	2.26	4.62	40	5
Coal	1	1380	0.74	2.22	0.60	1.91	25	2
Floor	50	2312	4.59	7.65	1.63	3.51	40	5

Figure 7.3 shows the numerical model plot of 60 m wide PWBP at Satgram Incline mine along with its mechanical and hydraulic boundary conditions. The mechanical model was prescribed a rigid boundary along the lower base of the floor and a roller boundary at the two vertical sides of the model. The hydraulic boundary considered the imposition of pore pressure corresponding to a water head of 84.5 m and saturated boundary condition at the reservoir-side modelled zone of interest (MZoI) covering 4m of immediate roof and floor and 2 m of pillar height. The permeable boundary conditions were assigned to the whole extent of MZoI on the reservoir side, while it was limited to the pillar and the associated horizontal planes in the roof and floor on the active working side. The remaining boundary on the active mine working side was considered impermeable for a better assessment of the behaviour of PWBP.

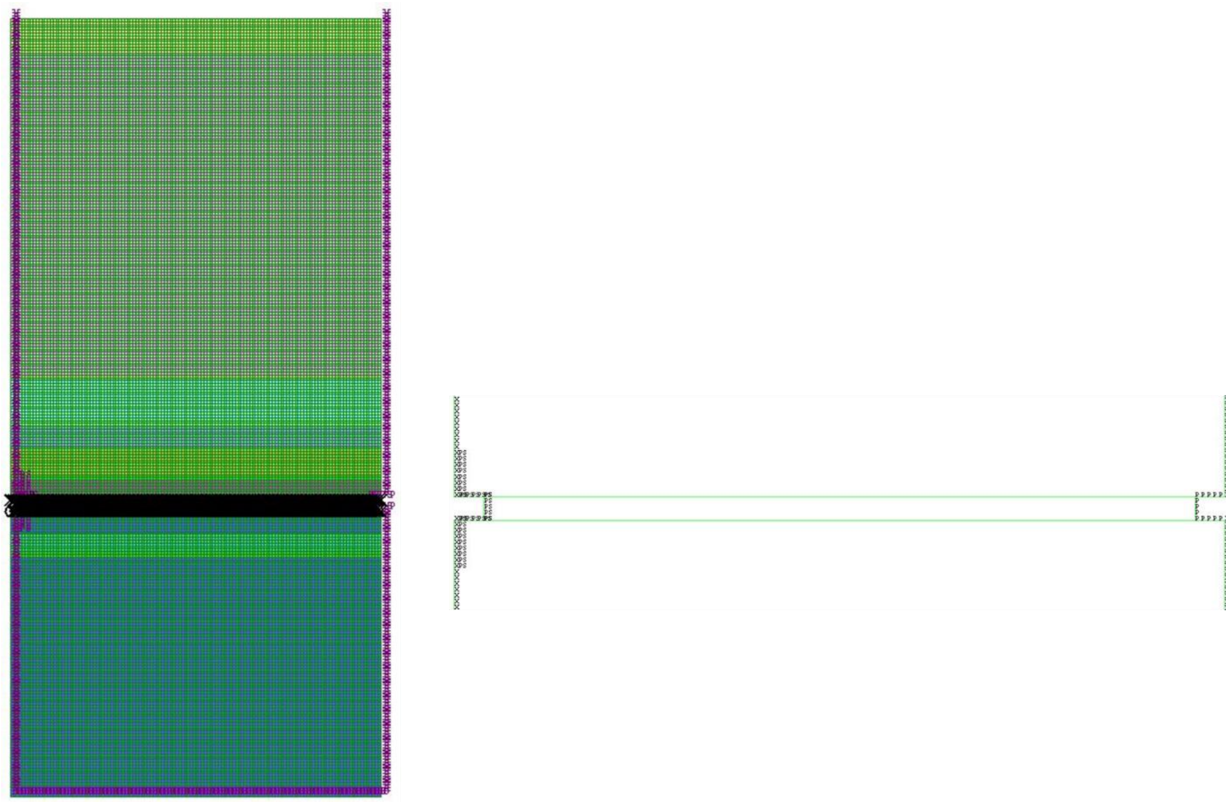
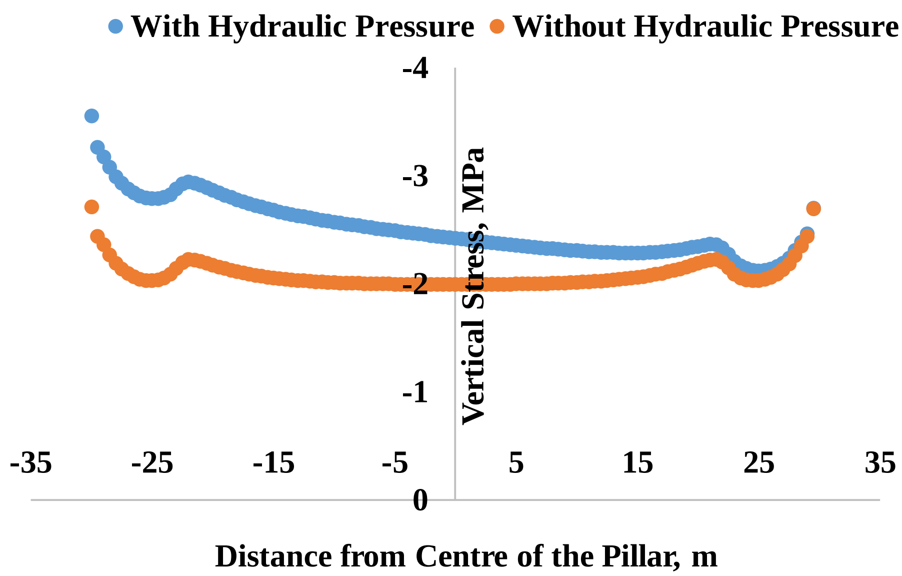
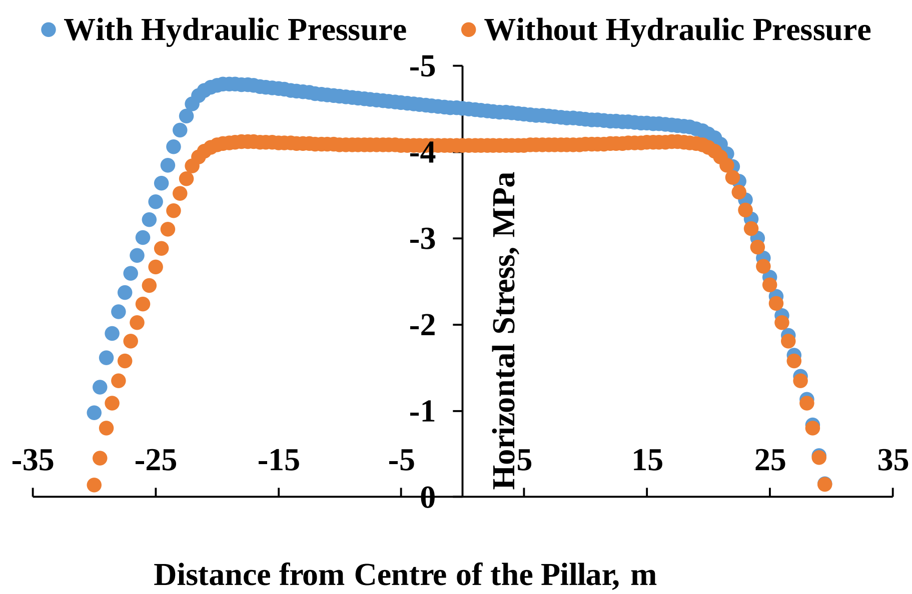


Figure 7.3. Numerical model of 60 m wide PWBP at Satgram Incline mine

The profile of induced stress upon the development of the pillar was symmetric in the mechanical loading condition. The induced vertical stress was higher at the corner of the pillar and decreased towards its core (Figure 7.4a). However, the confining stress was the least at the edges and followed an increasing trend till it stabilised in the core zone (Figure 7.4b). Upon imposition of the water head on the reservoir side of the pillar, induced pore pressure developed inside the PWBP following a linear trend with its maximum value at the reservoir side edge and minimum value on the other side of the pillar (Figure 7.5). The resultant effective induced vertical and horizontal stresses also became asymmetric, with higher values at the reservoir than at the active mine working side (Figure 7.4). It is similar to the findings noted in the parametric study.



(a)



(b)

Figure 7.4. Profile of vertical (a) and horizontal (b) stresses induced in the PWBP in mechanical and hydraulic loading conditions

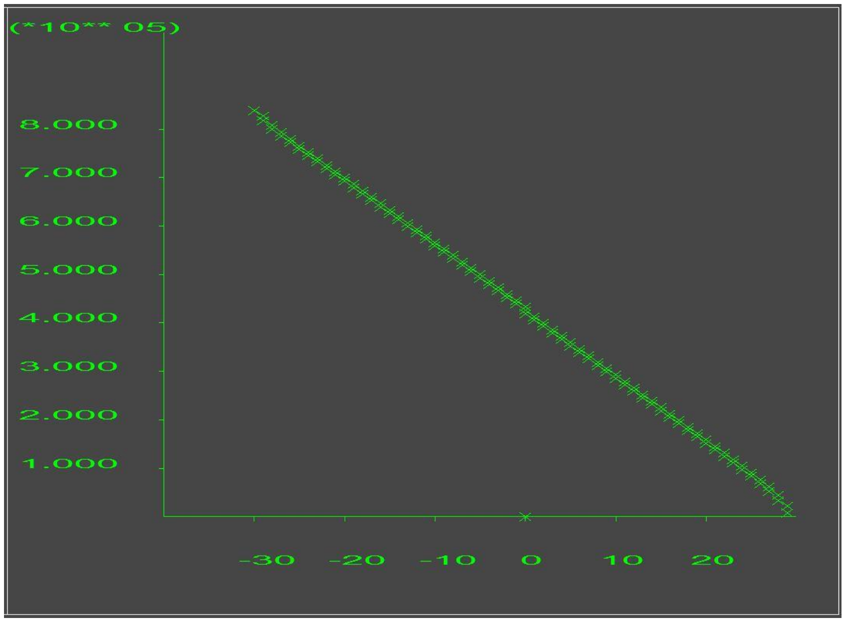


Figure 7.5. Pore pressure profile across the pillar

Figure 7.6 depicts the seepage rate pattern of water through the pillar and the adjoining immediate roof and floor towards the active working. The magnitude of the flow vector is maximum at the corner of the roof-pillar and pillar-floor contacts. The seepage rate shows a reducing trend with the increase in distance from the pillar edges along the roof and the floor. This is in line with the field observations.

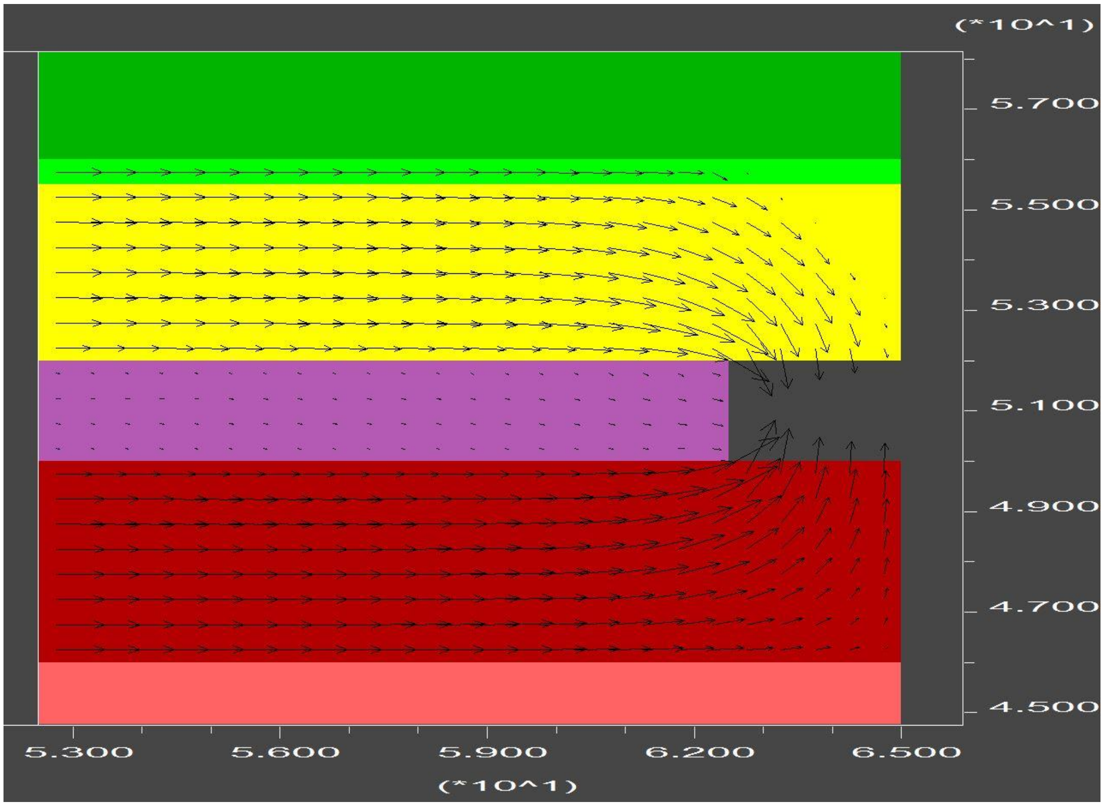


Figure 7.6. Flow vectors of water seepage in the PWBP at Satgram Incline mine

The ZoPVS for the 60 m wide barrier was 15.03 %, while the total seepage rate through the pillar system was 117.6×10^{-3} $m^3/s/km$ (1866.2 GPM/km) pillar against water head and cover depth of 84.5 m as prevailing in the mine. The contribution of the floor (30.6×10^{-3} $m^3/s/km$ (486.4 GPM/km)) in the total seepage rate was marginally higher than that of the roof (23.4×10^{-3} $m^3/s/km$ (370.7 GPM/km)), against the common observation owing to their different composition. The numerical modelling results corroborated well with the estimated ZoPVS of 15.28 % and the total seepage rate of 130×10^{-3} $m^3/s/km$ (2063 GPM/km) (Table 7.2). These outcomes confirm that the barrier pillar is mechanically stable, and the resultant seepage rate is moderately severe. These projections are in agreement with the field observation.

Table 7.2. Hydro-mechanical indicators of PWBP at Satgram Incline mine

Pillar Width, m	Cover depth, m	Water Head, m	Modelled ZoPVS, %	Estimated ZoPVS, %	Modelled seepage rate, $10^{-3}m^3/s/km$	Estimated seepage rate, $10^{-3}m^3/s/km$	Remarks
60	84.5	84.5	15.03	15.28	117.6	130	Moderate Severity

Figure 7.7 depicts the characteristic curves for ZoPVS and seepage rates for experimental widths of PWBP. The critical width corresponding to 100 % of ZoPVS, controlled seepage rate width corresponding to steady state flow of 315×10^{-3} $m^3/s/km$ (5000 GPM/km), and rational widths corresponding to 50% ZoPVS are 7, 22.8, and 15.5m, respectively, against the prevailing width of 60m in the field. All these indicators confirm a highly conservative and overdesign of the pillar in the prevailing condition. Failure to adopt rational pillar width at this mine is causing a huge loss of coal to the extent of 287 % with respect to the rational and 163 % w.r.t. to the controlled seepage rate width. Operating the mine for controlled seepage rate at the rational PWBP width would require controlling the maximum water head to 59.5 m. Such a strategy for the design of PWBP would have enabled the mine to unleash about 0.12 million ton of coal per kilometer of pillar length, which is to be permanently lost in the prevailing condition.

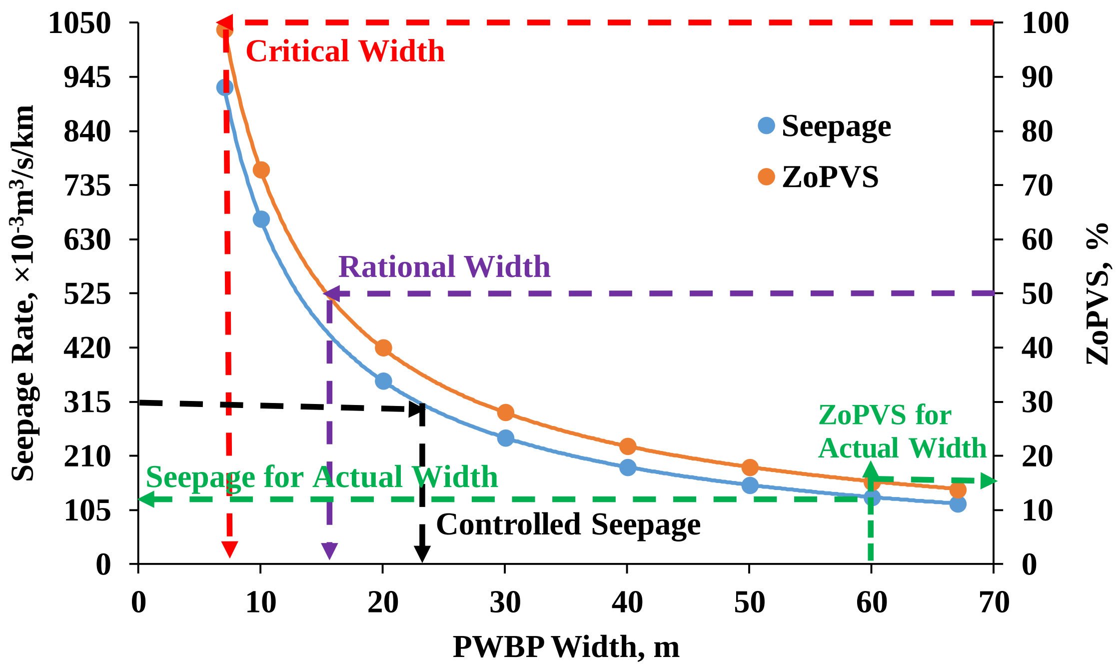


Figure 7.7. Seepage rate and ZoPVS for varying pillar width for Satgram incline

7.3 Lower Kenda Mine

The Lower Kenda mine is in Burdhwan district in the state of West Bengal, India and operates within the command area of Eastern Coalfields Limited. The leasehold area of 6.35 km^2 has been worked in three seams, namely, R-VII, R-VI, and R-V, at a cover depth of 57-170 m. At present, the mine is depillaring a 5.5 m thick R-V coal seam, which was developed using pillar width of 30 × 30 m width (centre-centre), extraction height of 3 m, and gallery width of 4.8 m. The seam was developed along its floor, leaving about 2.5 m thick coal in the roof. The cover depth of 134.5 m was recorded from the section of the borehole existing near the PWBP (Figure 7.8). The RMR of the immediate roof is 51-56.

The mine shares its boundary with the abandoned and waterlogged Haripur mine, which creates the problem of water seepage in the active mine. The pumping rate of the mine in the normal season is 151.2 $\times 10^{-3}$ m^3/s/km (2400 GPM), which increases to 226.8 $\times 10^{-3}$ m^3/s/km (3600 GPM) during the rainy season. The minimum inter-mine barrier width is 30 m, and it extends to 700 m along its length (Figure 7.8).

The rock mass properties of the coal seam and the associated roof and floor strata for this working are given in Table 7.3. The numerical model of PWBP for this mine considered a zone of influence of 6m in the roof and floor for the pillar height of 3 m for imposing the water head of 134.5 m at the given depth. The MZoI in the immediate roof is composed of 2.5 m coal and 3.5 m sandstone. On the other hand, the MZoI in the immediate floor consisted of 0.5 m coal sandwiched between 4 m and 1.5 m thick sandstone beds.

Table 7.3. Rock mass data for numerical modelling of Lower Kenda mine

Structure	Thickness, m	Density, kg/m^3	Shear mod., GPa	Bulk mod., GPa	σt, MPa	Cohesion, MPa	Friction angle, °	Dilation angle, °
Alluvium & Morrum	8.0	1775	0.27	0.45	0.06	0.10	40	5
Fine Grained Sandstone	11.5	2339	4.79	7.98	2.06	4.07	40	5
Coal	8.0	1380	0.74	2.22	0.60	1.91	25	2
Medium Grained Sandstone	58.0	2330	4.62	7.70	1.88	4.08	40	5
Coal	4.5	1380	0.74	2.22	0.60	1.91	25	2
Intercalation	36.5	2349	5.03	8.38	2.02	4.07	40	5
Coarse Grained Sandstone	5.5	2307	3.90	6.51	1.14	2.13	40	5
Coal	5.5	1380	0.74	2.22	0.60	1.91	25	2
Fine Grained Sandstone	4.0	2373	5.35	8.92	2.26	4.62	40	5
Coal	0.5	1380	0.74	2.22	0.60	1.91	25	2
Floor	45.5	2309	3.96	11.87	1.64	3.63	40	5

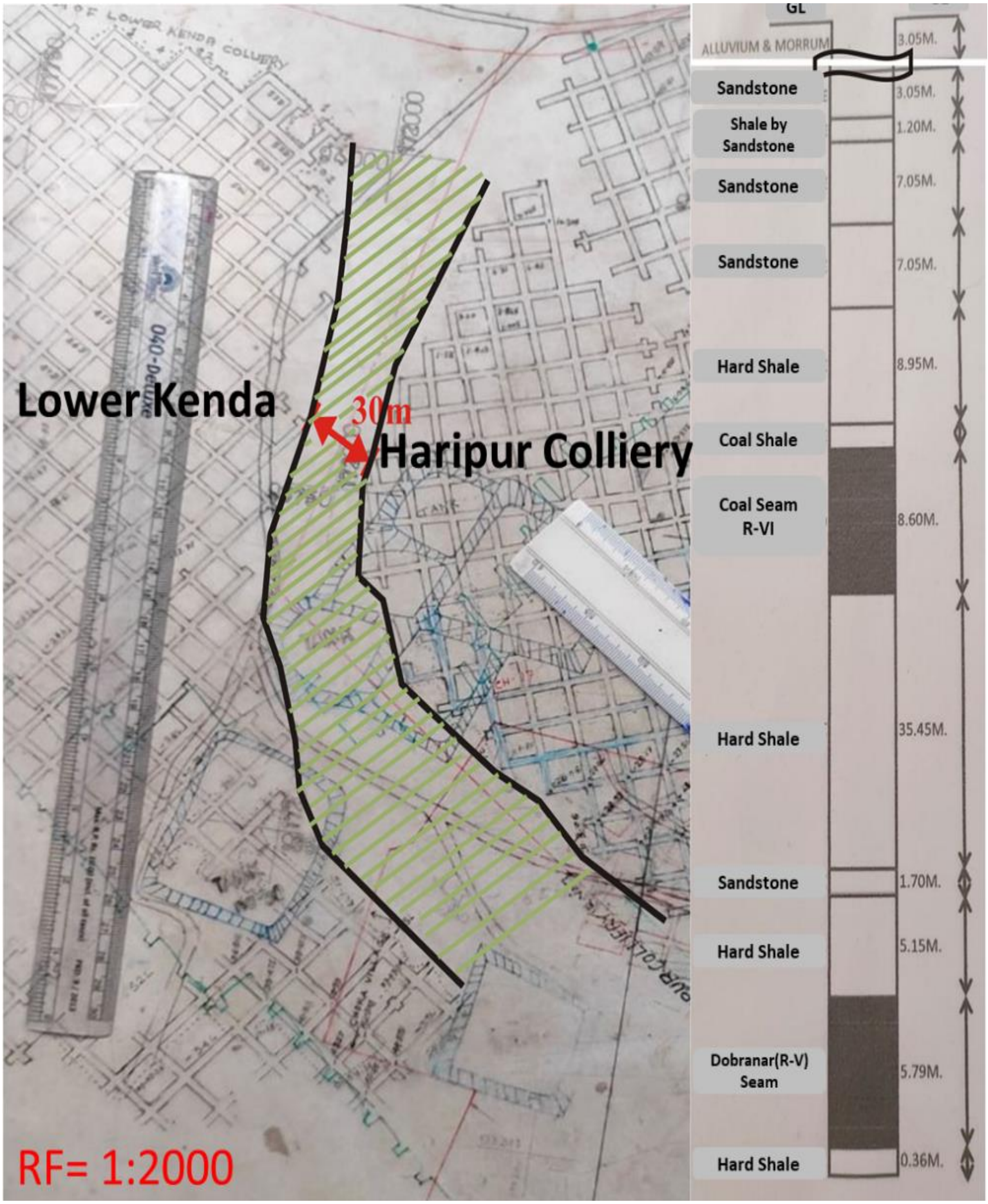


Figure 7.8. Joint mine plan showing the minimum barrier thickness of 30m between the Lower Kenda Mine and the abandoned waterlogged working of Haripur Colliery

The numerical model observed trends of vertical and horizontal stresses for mechanical and hydraulic loading conditions were similar to the Satgram Incline mine. A similar trend was noted for the pore pressure as well. Figure 7.9 shows the model plot of flow vectors on the active working side. The magnitude of the vector is maximum at the corner of the pillar and floor, which further confirms the greater seepage rate through the relatively more porous and permeable sandstone floor. On the roof side, the magnitude of the flow vector is maximum at the roof-pillar corner, signifying higher seepage rate through the contact surface. With the increasing distance from the corners along the roof and floor, the magnitude of the vectors gradually decreases. This is in line with the field observation, where the seepage rate is maximum at the corner and gradually decreases till it ceases. Further, the seepage rate through the floor (128.6×10^{-3} $m^3/s/km$ (2042 GPM/km)) was significantly greater than that through the roof (39.9×10^{-3} $m^3/s/km$ (632.8 GPM/km)). The significant difference in the seepage rate trends from the roof and the floor was attributed to their different compositions.

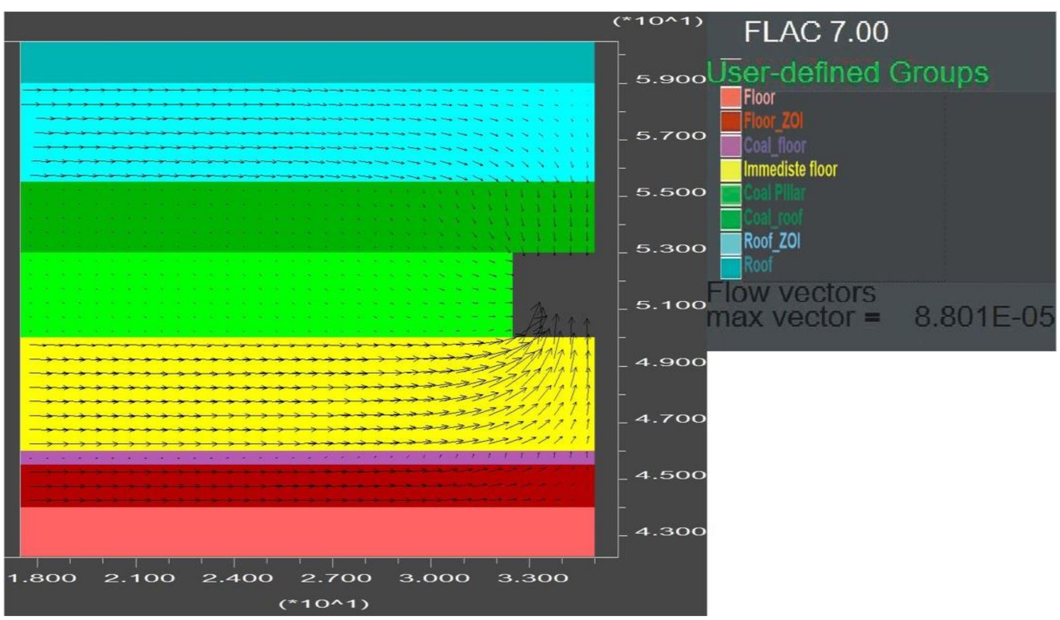


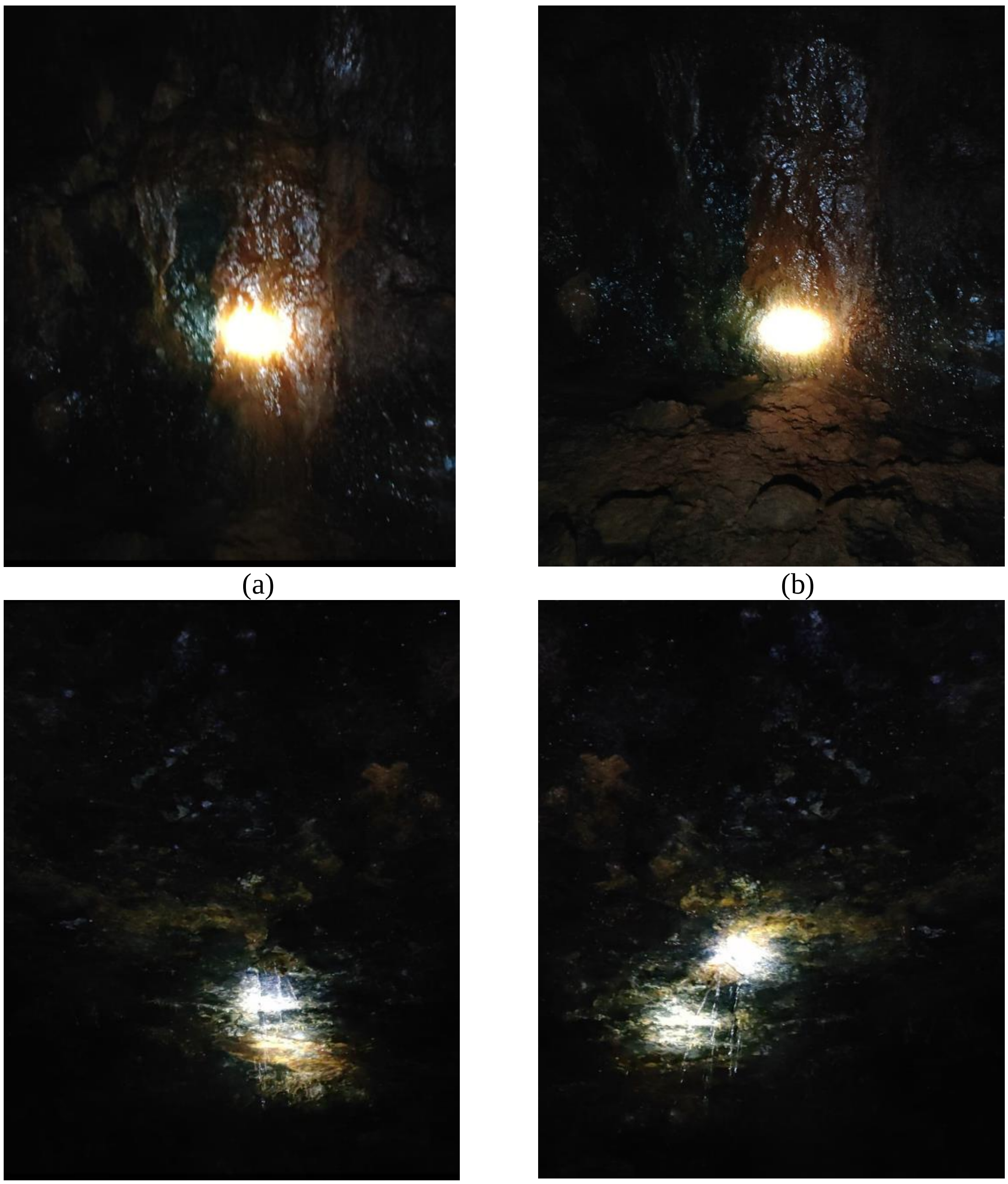
Figure 7.9. Seepage velocity vectors across the PWBP at Lower Kenda mine

The modelling results showed ZoPVS of 33.61 %, while the total seepage rate through the pillar system was 315×10^{-3} m^3/s/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 the pillar system of 338.3×10^{-3} m^3/s/km (5370 GPM/km) (Table 7.4). The estimated water seepage rate for the barrier pillar of 700 m length was 151.2×10^{-3} m^3/s (2399.3 GPM). The observed ZoPVS was much lower than its critical value indicating its stable behaviour. The seepage rate estimate showed a high severity of flooding in the mine for the minimum barrier pillar width of 30 m.

Table 7.4. Hydro-mechanical indicators of PWBP at Lower Kenda mine

Pillar Width, m	Cover Depth, m	Water Head, m	Modelled ZoPVS, %	Estimated ZoPVS, %	Modelled Seepage Rate, 10^{-3} m^3/s/km	Estimated Seepage Rate, 10^{-3} m^3/s/km	Remarks
30	134.5	134.5	33.61	37.86	315	338.3	High Severity

The visit of the underground mine in the region of PWBP in the non-rainy season confirmed significant seepage rate through the pillar in the rainy season (Figure 7.10), as indicated by the positioning of infill material that had washed out from the pillar-roof contact surface and deposited along the face of the pillar as well as the floor throughout the length of the barrier (Figure 7.10 a, b) as the rate of seepage slowed down with the lowering of the water head in the post-monsoon season. The water was dripping from the roof near the PWBP, even at the time of the field visit. The drip rate was higher in those regions where the width of the barrier was the minimum. The seepage was gushing through the roof bolts (Figure 10 c, d) as the hole drilled for the installation of roof bolts provided an easier channel for relief of excess water pressure. Several instances of flooding were reported in the past by the mine in the rainy season. The field observation pertaining to weathering of infill material along the interface confirmed the opinion of Lonnies (2017), suggesting a critical influence of the competency of interface material on the hydro-mechanical behaviour of the pillar.



(a) (b) (c) (d)

Figure 7.10. Seepage through coal pillar and washed out infill material (a,b) and gushing of water through roof bolts near PWBP (c,d) at Lower Kenda mine

The modelling result is combined with the site-specific data of average rainfall, rainfall infiltration factor, and the ratio of the mining area to the surface leasehold area to estimate the vertical infiltration of water in the Lower Kenda underground mine. Table 7.5 provides the estimate of vertical water seepage rate through overburden using Equation 2.25. The seepage rate from the barrier pillars has been estimated by deducting the vertical infiltration from the total makeup of mine water. Accordingly, the water seepage rate of 108.6×10^{-3} m^3/s/km (1724.3 GPM) was estimated through the pillar.

Table 7.5. Estimation of water seepage rate through overburden in Lower Kenda Mine

Specifics	**Values**
Leasehold area, m^2	6353300
Mineable area, m^2	5717970
Pit area, m^2	1143594
Average rainfall, m^3/Annum	11435940
Rainfall infiltration factor	0.06
Maximum feasible groundwater quantity, m^3/Annum	3430782
Vertical seepage rate through strata, 10^{-3} m^3/s	108.6

The width of the barrier pillar prevailing in the field has a variable width from 30-80 m over its 700 m length. The estimate of thickness weighted average seepage rate for this pillar dimension was 151.2×10^{-3} m^3/s (2399.3 GPM), while the total seepage rate in the mine was 259.8×10^{-3} m^3/s (4123.6 GPM). This make-up of mine water was significantly higher as compared to the installed pumping capacity of 226.8×10^{-3} m^3/s (3600 GPM) in the mine. The study revealed that the shortfall of pumping capacity by about 33×10^{-3} m^3/s (524 GPM) was causing periodical flooding of the mine whenever the water head was getting higher during the monsoon period.

Figure 7.11 shows the characteristic curve of ZoPVS and steady-state seepage rate for varying pillar widths. The critical, controlled seepage rate, and rational pillar widths are 9.8, 32.4, and 21.8 m, respectively, for this mine. Adopting the rational pillar width and controlling the maximum water head to 94 m could have provided an additional coal recovery of 0.03 MT/km of pillar length.

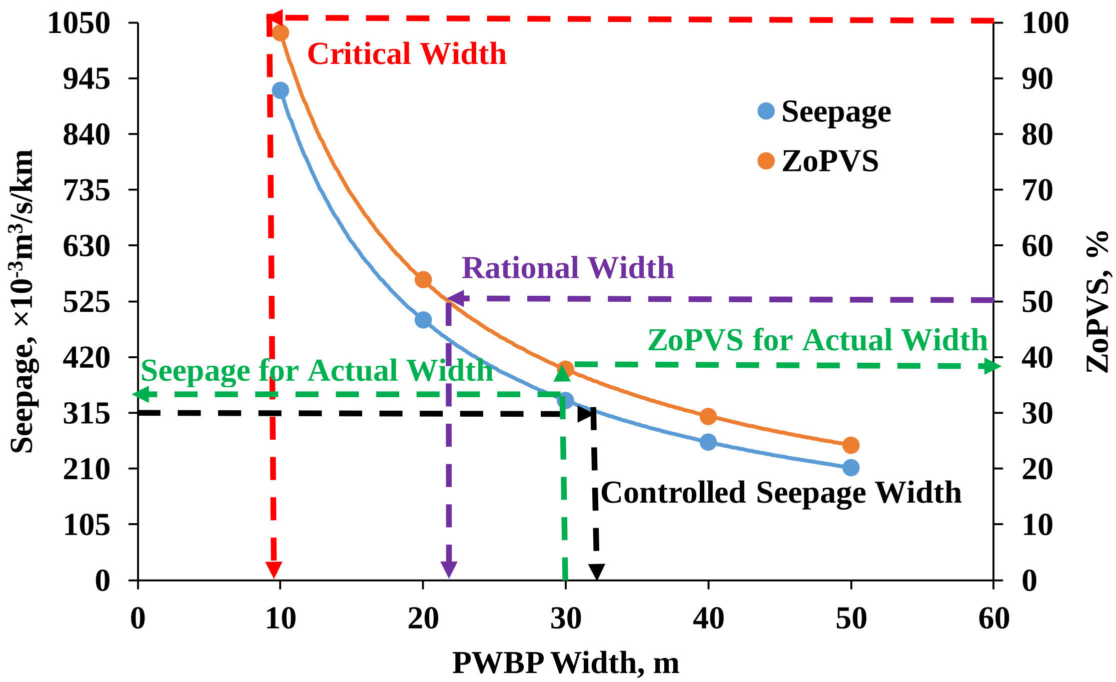


Figure 7.11. Seepage rate and ZoPVS for varying pillar width for Lower Kenda mine

7.4 Summary

The approach for assessment of hydro-mechanical performance and the criteria for the design of rational PWBP were validated for two case studies pertaining to Satgram Incline and Lower Kenda coal mines in Raniganj Coalfield. The Satgram Incline mine is working the

Dishergarh (R-IV) seam at a cover depth of 65-130 m. The immediate roof of the coal seam is formed of shale and intercalation rocks, whereas the floor was of fine-grain sandstone. The minimum width of the 2m high inter-mine barrier is 60 m, which extends along the length to a distance of 800 m. The maximum cover depth of the PWBP is 84.5 m.

The seepage rate pattern of water through the pillar and the adjoining immediate roof and floor towards the active working showed the maximum flow at the corner of the roof-pillar and pillar-floor contacts. The seepage rate showed a reducing trend with the increase in distance from the pillar edges along the roof and the floor, which is in line with the field observations. The ZoPVS for the 60 m wide barrier was 15.03 %, while the total seepage rate through the pillar system was 117.6×10^{-3} m^3/s/km (1866.2 GPM/km) pillar against water head and cover depth of 84.5 m as prevailing in the mine. The contribution of the floor (30.6 $\times 10^{-3}$ m^3/s/km (486.4 GPM/km)) in the total seepage rate was marginally higher than that of the roof (23.4×10^{-3} m^3/s/km (370.7 GPM/km)), against the common observation owing to their different composition. The numerical modelling results corroborated well with the estimated ZoPVS of 15.28 % and the total seepage rate of 130×10^{-3} m^3/s/km (2063 GPM/km). These outcomes confirm that the barrier pillar is mechanically stable and the resultant seepage rate is of ‘moderate severity’. These projections are in agreement with the field observation.

The critical width corresponding to 100 % of ZoPVS was only 7m, while the controlled seepage rate width corresponding to steady state flow of 315×10^{-3} m^3/s/km (5000 GPM/km) was 22.8 m. The rational widths corresponding to 50% ZoPVS was 15.5 m against the prevailing width of 60m in the field. All these indicators confirm a highly conservative and overdesigned pillar in the prevailing condition. Failure to adopt rational pillar width at this mine is causing loss a huge loss of coal with respect to the rational and the controlled seepage rate width. Operating the mine for controlled seepage rate at rational width of PWBP would require controlling the maximum water head to 59.5 m.

The depillaring working in seam V of Lower Kenda mine shares its boundary with the waterlogged Haripur mine with the PWBP of 30 m width at the cover depth of 134.5 m. The pumping rate of the mine in the normal season is 151.2×10^{-3} m^3/s (2400 GPM), which increases to 226.8×10^{-3} m^3/s (3600 GPM) during the rainy season. The numerical model observed trends of induced stresses, and the pore pressure induced in the pillar for mechanical and hydraulic loading conditions was similar to the Satgram Incline mine.

The magnitude of seepage rate was maximum at the corner of the pillar and floor, which confirmed greater seepage through the relatively more porous and permeable sandstone floor. The seepage rate of 128.6×10^{-3} $m^3/s/km$ (2042 GPM/km) through the floor was significantly greater than 39.9×10^{-3} $m^3/s/km$ (632.8 GPM/km) through the roof. The significant difference in the seepage rate trends from the roof and the floor was attributed to their different compositions. On the roof side, the magnitude of the flow vector was maximum at the roof-pillar corner, signifying higher seepage rate through the contact surface. With the increasing distance from the corners along the roof and floor, the magnitude of the vectors gradually decreased.

The modelling results showed ZoPVS of 33.61 %, while the total seepage rate through the pillar system was 315×10^{-3} $m^3/s/km$ (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 the pillar system of 338.3×10^{-3} $m^3/s/km$ (5370 GPM/km). The observed ZoPVS was much lower compared to its critical value indicating its stable behaviour. The results indicated a ‘high severity’ of seepage rate causing periodic flooding in the mine for the minimum barrier pillar width of 30 m. The field observation confirmed the observations of Lonnies (2017), suggesting a critical influence of the competency of interface material on the hydro-mechanical behaviour of the pillar. The critical, controlled seepage rate, and rational pillar widths were 9.8, 32.4, and 21.8 m, respectively, for this mine. Adoption of rational pillar width will require control of maximum water head to 94 m at this mine.