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Proceeding Paper

A Generalized Numerical Simulation Calibration Approach to Predict the Geotechnical Hazards of a Coal Mine: Case Study on Khalashpir Coal Basin, Bangladesh †

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Abstract: Numerical investigation facilitates the development and exploitation phase of a coal mine, incorporating geological settings by forecasting the overall stability. This study proposes a generalized numerical simulation calibration approach to predict potential geotechnical hazards in an explored coal mine, focusing on the Khalashpir coal basin in Bangladesh. This research investigates the feasibility of initiating mining at the central block, which is associated with major faults by the finite element method (FEM), which is a valuable tool for understanding the variations of stress distribution in the rock mass. The study verifies the findings of the FEM by further assessing the seam convergence, vertical stress, and strain safety factor using the boundary element method (BEM), which involves numerical discretization in a reduced spatial dimension. The results illustrate that there will be significant displacements in the formation, which infer subsidence and increase vastly along the fault lines. This numerical investigation approach provides essential insights for future research concerning newly explored coal mines, particularly ones in the Gondwana basin.

Keywords: mine structure modeling and monitoring; geohazard susceptivity; numerical risk analyses; vacuum triaxial tests; Khalashpir coal basin

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1. Introduction

Understanding the stress pattern, mine-induced stress redistribution, seam convergence, and strength parameter alteration is crucial for mine design, especially for the design of the underground support system, panel, and pillar dimension. A proper sequential design program from the initial mine entry development to the final economic extraction stage can ensure a safe and efficient mining operation during the exploration period. Although empirical models developed from field and laboratory-derived data were initially used for underground mine design, many numerical schemes incorporating measured mechanical properties have also been developed recently that can precisely investigate mining situations under complex geological and boundary conditions [1]. This study demonstrates the modeling and stability analysis of an explored minefield, the Khalashpir coal mine, Bangladesh, utilizing two numerical methods: the finite element method and the boundary element method. It investigates the laboratory strength parameters, the two methods' comparative results, and the impact of geological constraints and water on the overall mine stability during mine development.

Khalashpir Coal Basin

The Khalashpir coalfield, one of five coal fields discovered in Bangladesh, is in the northwestern part of Bangladesh. Two consortiums, named Hosaf International Limited and Shandong-Ludi Xinwen Mining Group, have explored the coalfield extensively following the Geological Survey of Bangladesh (GSB) discovery in 1989. The GSB has found significant coal accumulation in three out of four drilled boreholes at depths ranging from 257.16 m to 484.15 m [2]. The Hosaf and CMC's collaborative work under the Ministry of Power, Energy, and Mineral Resources (MPEMR) has proposed mine planning and construction procedures based on 17 borehole data points. Following analyses of the 2D and 3D seismic data to evaluate the geologic succession, groundwater, and location of the coal basin faults, the work measures the reserve of the coal basin using the thickness area method, and proposes the longwall mining method and shaft locations [3,4]. Later, to validate the study of the venture, MPEMR collaborated with a local company, IMC [5]. Both feasibility studies suggest that the coal basin's initial production should commence at the central block of the coal basin.

The Permian-aged Gondwana group hosts high-ranked bituminous coal distributed in eight seams, as the oldest rock encountered in most boreholes. The formation has very low permeability (0.64–0.067 m/day), and the water accumulation associated with the coal seam is not considerable [6]. Immediately above the Gondwana formation, the Miocene-aged Surma formation has nearly the same hydrological characteristics and consists of alternating beds of sandstone and mudstone, and shale [7,8]. However, the overlying aquifer belonging to the DupiTila formation of the Pliocene age severely influences this region's mining activity [9]. The only active coalfield in the adjacent area, the Barapukuria coal mine, has an identical stratigraphic succession and faced major water inrush at the development stage, and the construction was abandoned for two years [10]. The average thickness of the DupiTila aquifer is 125 m in the Khalashpir coal basin and is highly permeable (32.10–42.20 m/day), and the aquifer consists of unconsolidated fine to coarse-grained sandstone and will play a vital role in the mine development phase due to the notion that the large aquifer is well above the coal seams [11]. Farazi and Quamruzzaman (2013) validated the shaft sinking method suggested by the joint venture using empirical correlations [9]. Islam et al. (2019) predicted the discharge velocity of the water inrush of the coal basin using the boundary element numerical simulation technique, as well as the results of this coverage on the initial stage settings discharge scenario of this research that estimates the discharge velocity using the finite element method [12]. The Khalashpir coal basin is divided into five blocks. The blocks are the central block, east block, south block, north-east block, and west and north-west block, with reserves of 136.28 mt, 40 mt, 28.33 mt, 17.39 mt 79.70 mt, respectively. The existing literature contains no comparative numerical study on stability analysis, which is imperative for mine development and exploitation. The main objective of this research is to demonstrate a generalized numerical simulation calibration approach and predict the possibility of geotechnical hazards in the Khalishpir coal basin.

2. Finite Element Method (FEM) Analysis

The finite element method is utilized for stress distribution and redistribution assessment in the structural analysis of irregular geometry with loading or complex boundary conditions. FEM discretizes the domain rock mass into several elements, connects each element to one other using a common node point, assigns governing equations at each node, performs the precise polynomial interpolation of the physical quantities from one node point to another over the entire domain, and eventually yields a closed-form solution. However, the FEM model gives an approximate solution with a higher degree of error [13].

2.1. Longwall Unit Specifications

Table 1 shows the parameters and specifications for the finite element method analysis of the central block of the Khalashpir coal basin [14,15].

Table 1. Parameters and specifications for the finite element method.

Parameters	Specifications
Main shaft	Diameter of 8 m
Auxiliary shaft	Diameter of 8 m
Tunnel 1 (horseshoe)	The radius of 2.5 m and height of 5.2 m
Tunnel 2 (horseshoe)	The radius of 2.5 m and height of 5.2 m
Extraction height	3 m.
Advance per shear	0.6 m (app.)
Surface distributed load over 200m (app.)	0.02 MN/m^2

For this research, 13 boreholes' data are used (Figure 1), including GDH-45, GDH-46, GDH-47, GTB-3, GTB-4, GTB-6, GTB-9, GTB-12, GTB-16, GTB-18, GTB-19, GTB-20, and GTB-21.

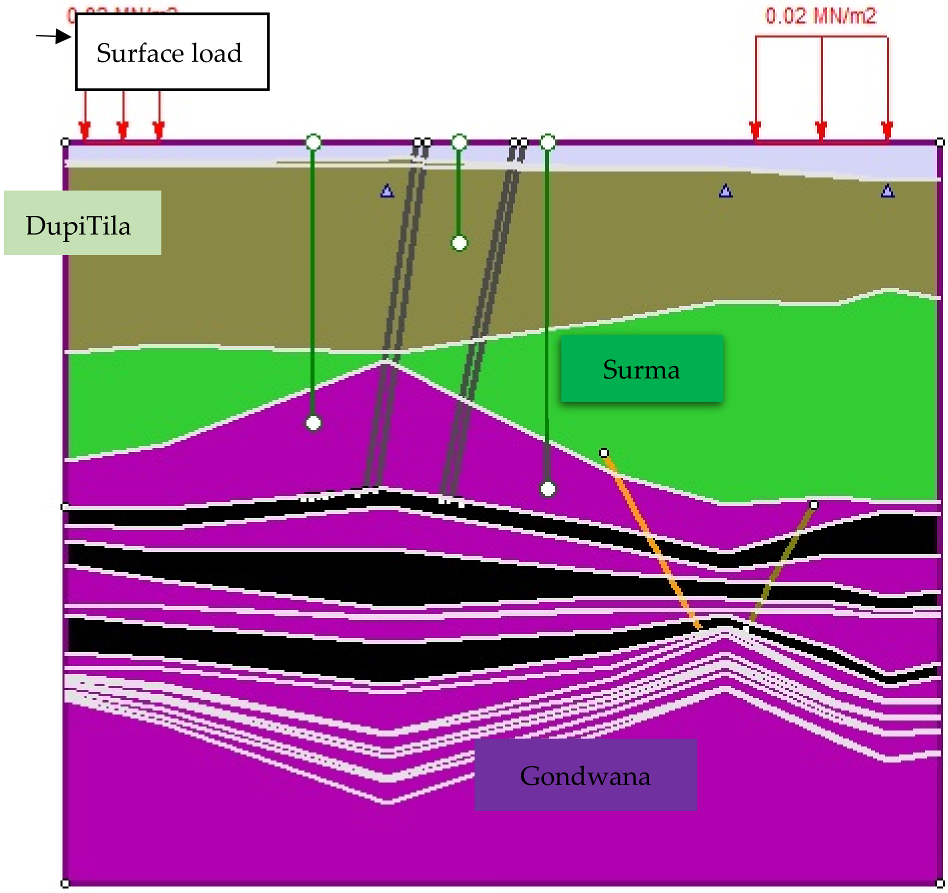


Figure 1. A cross-sectional view of the coal basin profile with 13 boreholes' data where whitish ash, light orange, olive green, light green, violet, and black indicate alluvium deposits, Madhupur clay, DupiTila formation, Surma group, Gondwana group, and coal, respectively.

Within the study area, the F1 and F6 joints (Figure 2) are located with a distance of more than 150 m and 100 m, respectively, with reference to the borehole of the GDH-46 [7].

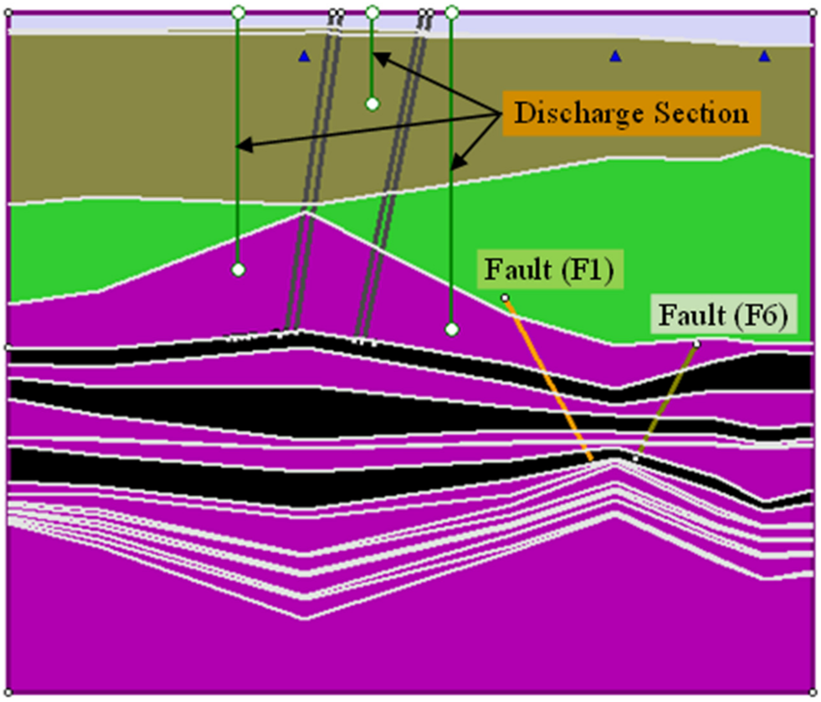


Figure 2. Cross-sectional geometry for the finite element method representing three discharge sections and faults over 50 hectares of land.

2.2. Stage Settings

This study involves establishing seven stages (Table 2), including the initial, surface load, main shaft, auxiliary shaft, tunnel 1, tunnel 2, and recovery phase of five longwall panels. Figure 3 shows the initial, surface load, main shaft, and recovery stage.

Table 2. Stage settings.

Name	Time (Days)	Drained	PWP Method
Initial	0	Fully Drained	Steady State
Surface Load	160	Drained	Coupled
Main Shaft	710	Drained	Coupled
Auxiliary Shaft	1260	Drained	Coupled
Tunnel 1	1400	Drained	Coupled
Tunnel2	1600	Drained	Coupled
Recovery	1650	Drained	Coupled

2.3. Material Properties

In this study, the material properties are considered based on the formation's depth, geologic and hydrogeologic conditions, laboratory tests, and rock mass classification [16]. The primary purpose of investigating the rocks' mechanical properties is to assess the subsurface condition of the mine [15].

For each stratigraphic segment, the following properties are taken into account: unit weight, initial water condition, Poisson's ratio, Young's modulus, peak friction angle, peak tensile strength, cohesion, fluid bulk modulus, and porosity. The value of the unit weight, initial water condition, Poisson's ratio, Young's modulus, peak tensile strength, and cohesion are available from the tested borehole samples [3]. The fluid bulk modulus value is calculated using the elastic modulus and cohesion value [17]. The porosity value of Khalashpir coal basin is predicted by correlating with the other nearby Gondwana coal basins, considering the depth, groundwater conditions, fault locations, and other geotechnical parameters [18].

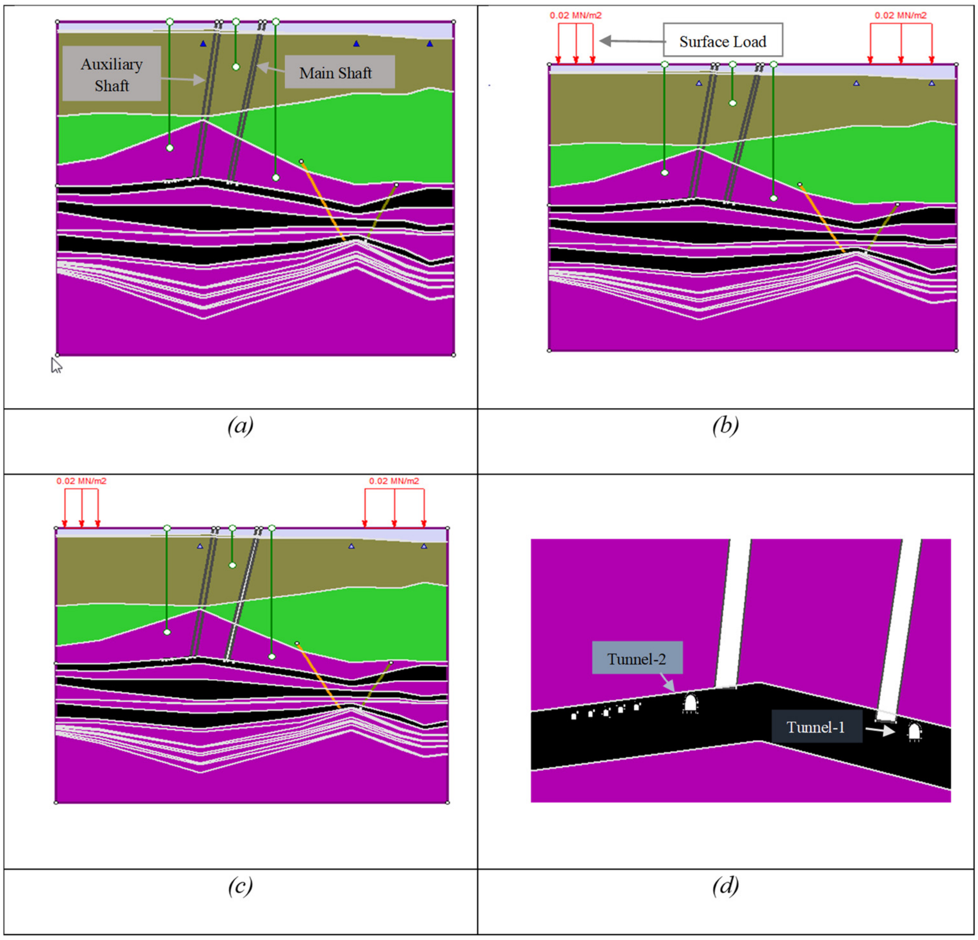


Figure 3. Stages in mine development. (**a**) Initial stage with shaft locations at 60 m apart at 60-degree angles. (**b**) Surface load stage with two 0.02 MN/m^2 loads for building areas over the mine. (**c**) Main shaft construction stage. (**d**) Recovery stage denoting cross-sectional view of mine after two shafts, two tunnels (coal recovered), and five panels' construction.

3. Boundary Element Method (BEM) Analysis

The boundary element method provides the numerical approximation of the boundary value problems through the solution of the boundary integral equation [19,20]. Using BEM, boundary-dependent physical data of a system related implicitly to the domain can be determined more accurately. Moreover, the BEM method only discretizes the boundary, and the domain's interior solution has a higher convergence rate [21–23]. Nevertheless, inhomogeneities of the rock mass, a nonlinear governing differential equation, a discontinuous boundary condition, possibilities of diverse boundary integral equations at the boundary, and pseudodifferential operators for resolving the Kernel's singularities of the integral equation may intensify the mathematical complexities in BEM [24].

3.1. Longwall Unit Specifications

The parameters and specifications for the boundary element method analysis of the central block of coal seam I of the Khalashpir coal basin are shown in Table 3 (Figure 4).

Table 3. Longwall unit specifications.

Parameters	Specifications
Main shaft	Diameter of 8 m
Auxiliary shaft	Diameter of 8 m
Extraction height	3 m
Advance per shear	0.6 m (app.)
Longwall panels	120 m

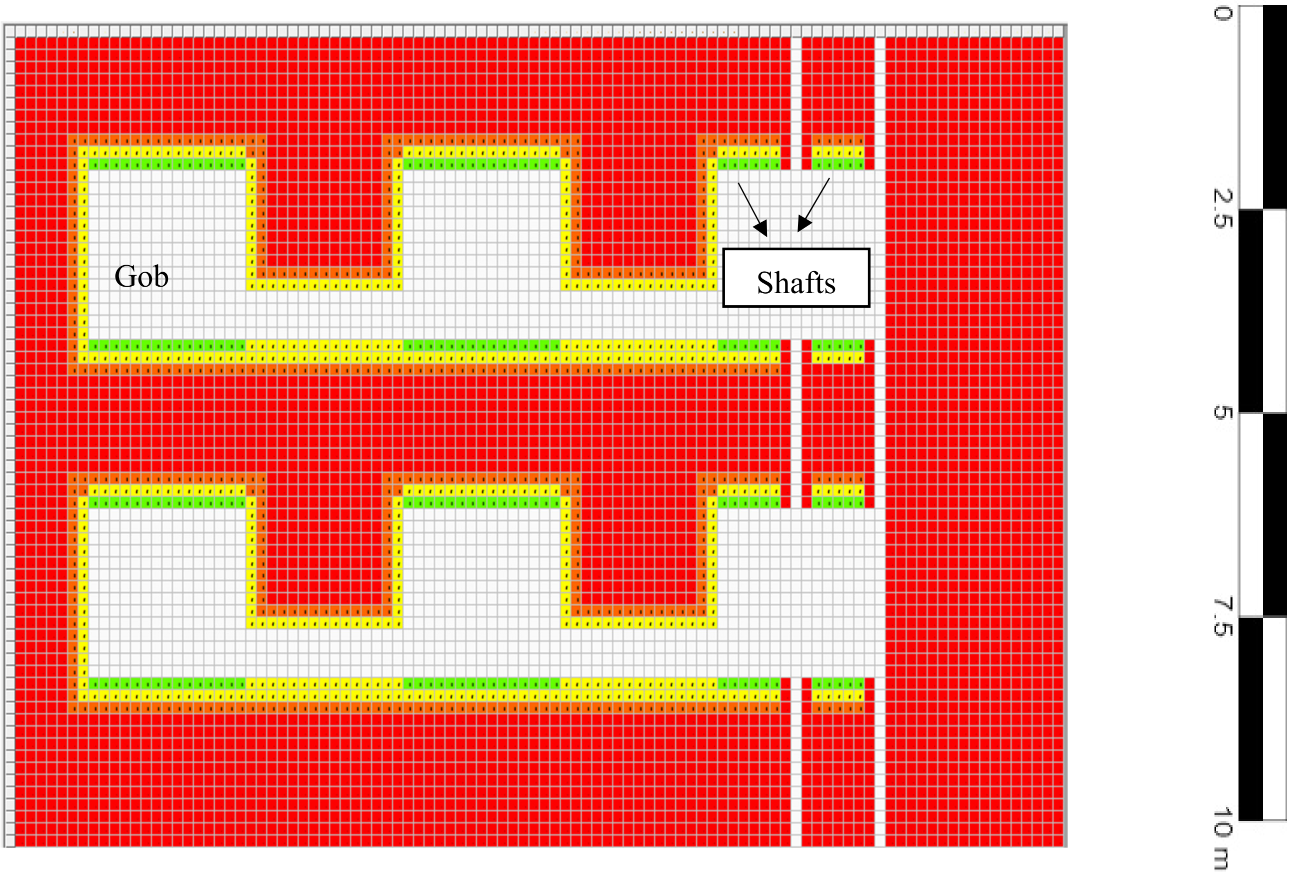


Figure 4. Cross-sectional laminated model of the coal seam I in a grid view with two 8 m shafts, where red zones indicate the coal zone at 240 m from the surface with two 8 m shafts. (Scale bar 7:1).

3.2. Material Properties

An RMR value of 50 was employed for the Khalashpir coal basin based on the depth and geologic and hydrogeologic condition by correlating with the other Gondwana coal basins. The RMR and rock mass modulus relationship of Beinwiawski and the RMR value of 50 correspond to 13,000 MPa [25]. The concept of lamination thickness is that the coal is interpreted using a large number of grids to assess vertical stress, seam convergence, and strain safety factors using governing equations and statistical methods. Table 4 tabulates the properties of the lamination wizard. In this case, seam I with a thickness of 10 m is considered to be 70 m in 70 grids along the y-axis. The coal is considered to exhibit an elastic-plastic behavior, and the strain-hardening gob is the most appropriate fit for this case (Table 5) [26].

Table 4. Properties of the laminated model.

Criteria	Parameter	Value
Geometry parameters	Seam number	1
	Extraction thickness (m)	3
	Element width (m)	8
Coal properties	Coal modulus (MPa)	3700
	Plastic modulus (MPa)	0
	Coal strength (MPa)	6.205
Yield zone definition	Number of the set to be defined	1
	Number of yield zones per set	1
	Total number of materials required	3
Rock mass parameters	Poisson's ratio	0.25
	Elastic modulus (MPa)	13000
	Lamination (layer) thickness (m)	70
	Vertical stress gradient (MPa/m)	0.025448
	Overburden depth (m)	240
Gob properties	Number of gob materials	1
	Width of gob area (m)	120
	% Overburden load on gob	0.325636
	Initial gob modulus (MPa)	0.6896
	Upper limit stress for gob (MPa)	27.58
	Gob height factor	1
	Final modulus for gob (MPa)	15,919.53324777

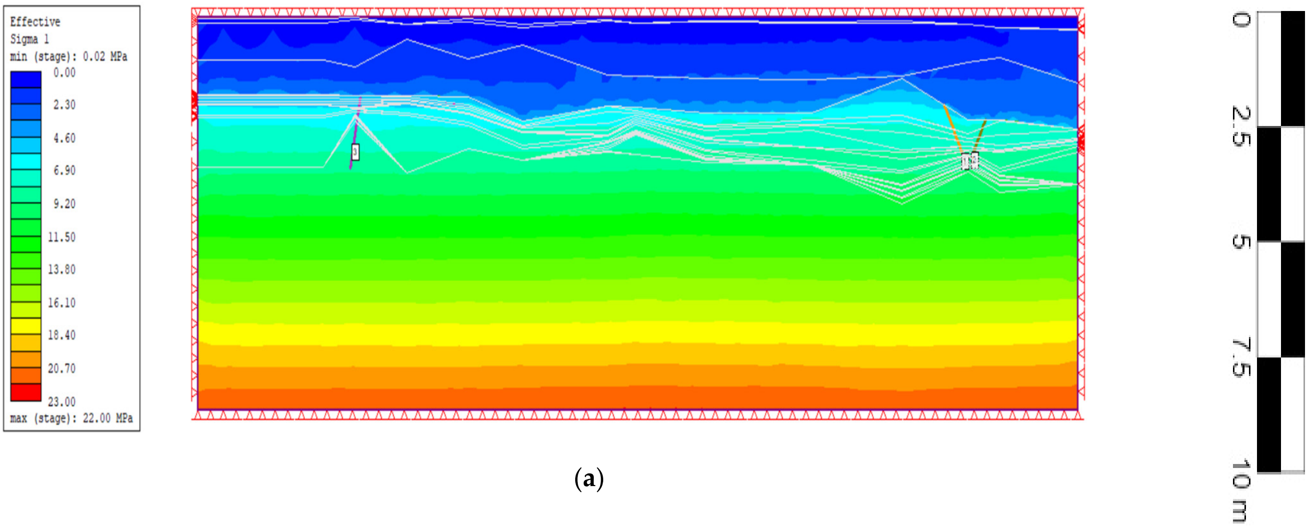
Table 5. Four materials of the laminated model.

Material	Model Type	Parameter: Initial	Parameter: Final
Coal	Linear elastic	3700	0.33
Coal	Elastic-plastic	21.8416	0.00590314
Coal	Elastic-plastic	15.8848	0.00429319
Gob	Strain hardening	0.6895	15,919.5

4. Model Results and Analysis

4.1. Variations in Stress Redistribution

The Mohr–Coulomb criterion is a set of linear equations in principal stress space describing the conditions for which the isotropic materials will fail, which is expressed as a function of Φ_1 and Φ_3 and a widely accepted failure criterion to simulate geotechnical hazards [27,28]. This case study applies the Mohr–Coulomb failure criterion in both the finite element method (FEM) and boundary element method (BEM) to generate the major principal stress (Φ_1) and minor principal stress (Φ_3) using the RS2 finite element package and total vertical stress through the calibration of LaModel, which is a boundary element package, respectively. The RS2 finite element model shows Φ_1 and Φ_3 (Figure 5) values of the initial stage at steady-state groundwater conditions. The total vertical stress can be calculated from the figures at any depth by averaging Φ_1 and Φ_3. The estimated total vertical stress is 9.5 MPa at a depth of 245 m from the surface, denoting the longwall retreat's edge.



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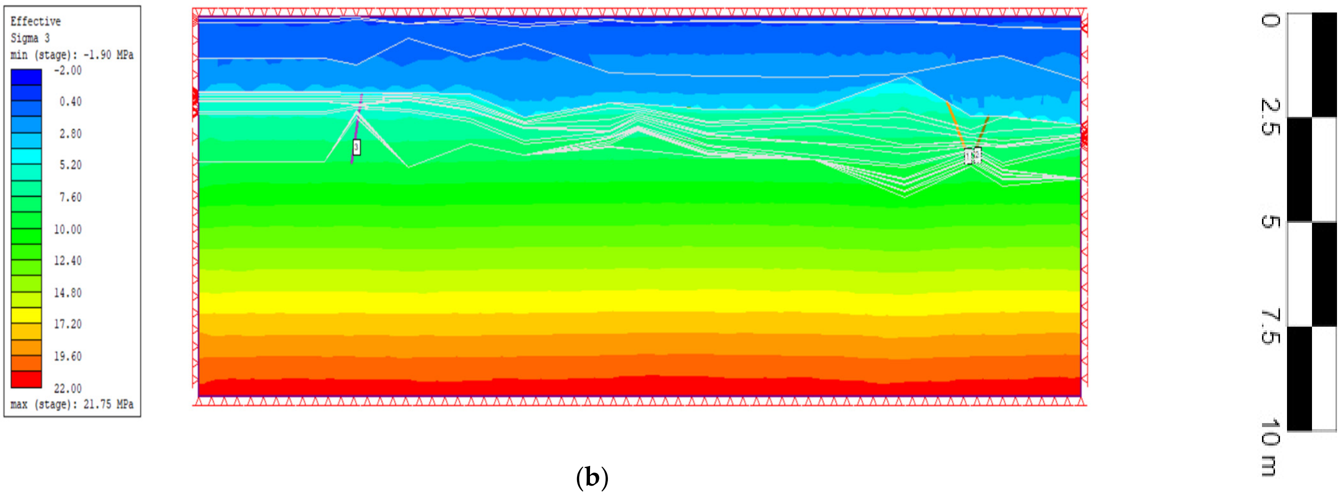

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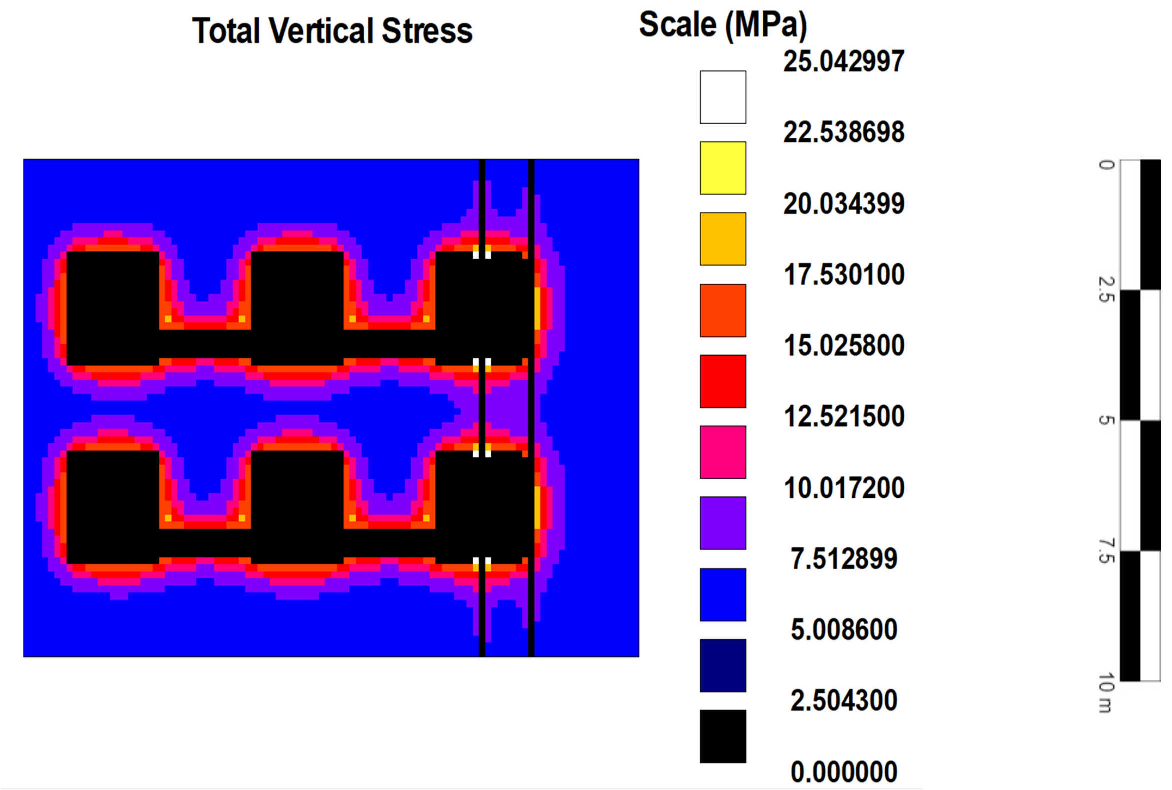
Figure 5. (**a**) Spatio-temporal major principal stress (Φ_1) denoting mean 11 MPa at coal zones. (**b**) Spatio-temporal minor principal stress (Φ_3) denoting mean 8 MPa at coal zones (scale bar 1:55.38).

The boundary element package LaModel simulates the total vertical stress, which combines overburden load, multiple seam stress, and abutment load, utilizing an empirical equation developed by Heasley [29]. The total vertical stress plots show that the stress in the supported zones is lowest and increases significantly with longwall retreat (Figure 6). At a depth of 245 m, the total vertical stress is observed to be 25 MPa.

The vertical stress due to the longwall retreat changed from 9.9 MPa at the initial state to 25 MPa after the extraction process, resulting in an increase of 152% in MPa. The vertical stress values also agreed with the stress distribution of the Barapukuria coal mine, which has similar geologic settings to the Khalashpir Coal Basin [10]. The value elevates intensely when the extraction is performed. For the construction of shafts in such hydrological conditions, the freezing technique can be applied. Nevertheless, the technique is very expensive and requires substantial investment in the construction phase.

4.2. Seam Convergence

The characteristics of slope displacements can be assessed by predicting horizontal and vertical displacements caused by the weight of the body and acting on the slopes and caves [30]. The movements of rock strata can be described as horizontal and vertical displacements that largely vary due to the magnitude of the modulus of elasticity [31].



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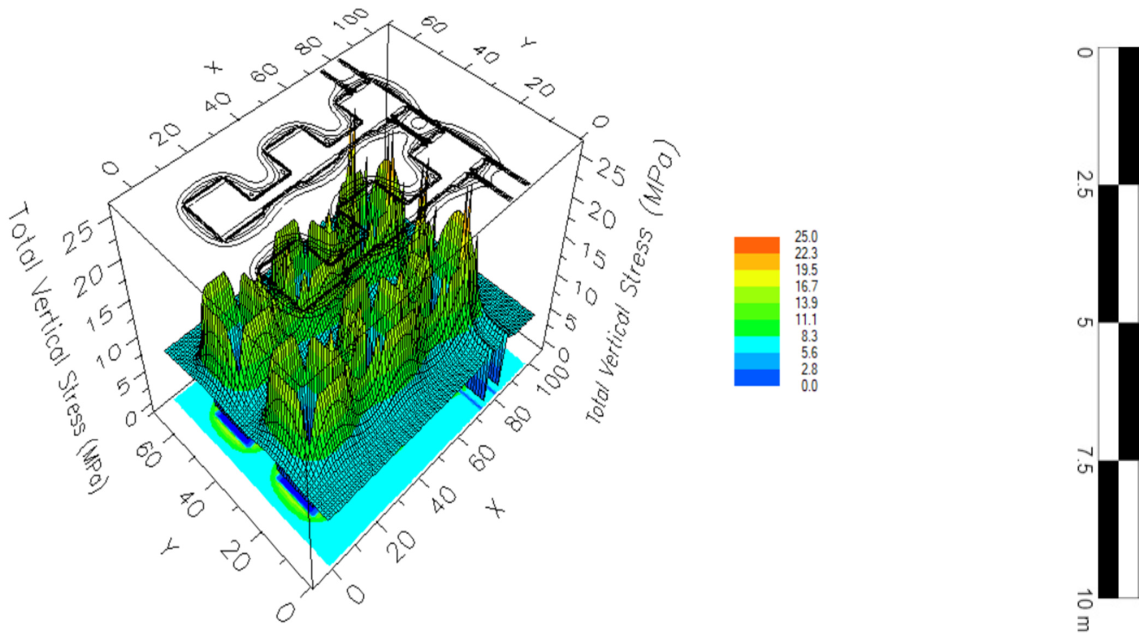

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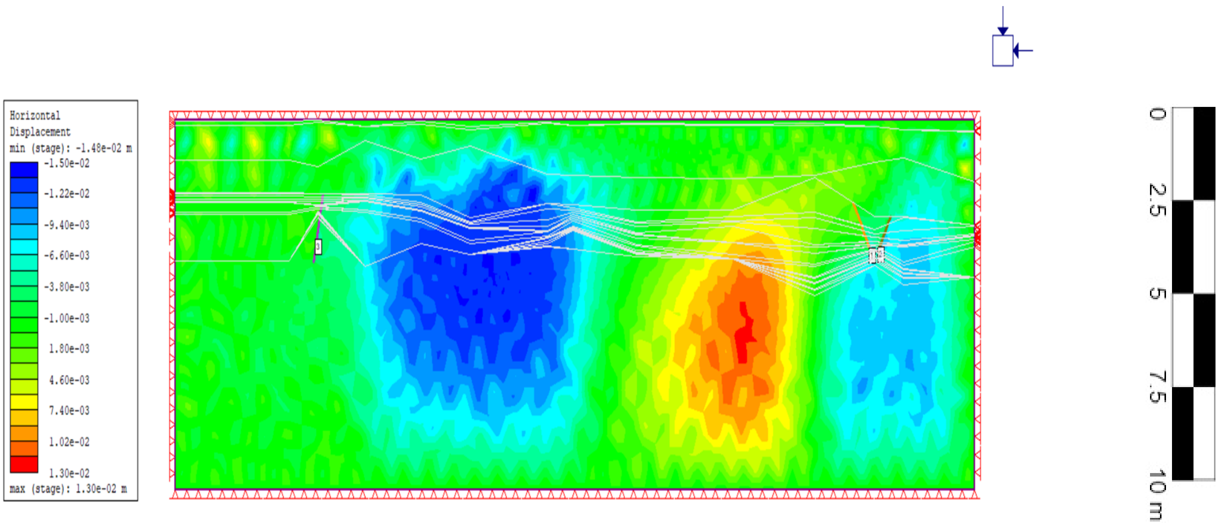
Figure 6. (**a**) Total vertical stress in coal seam 1 in the square plot using an equation developed by Heasley. (**b**) Total vertical stress in the 3D fishnet plot using regression analysis (scale bar 7:1).

Figure 7 represents the horizontal and vertical displacements of the initial stage of the rock formation by the finite element method (FEM). The results assert the maximum horizontal and vertical displacements near the fault zones, and the displacements gradually reduce as they move from the fault zones. The total seam convergence calculated using

Pythagoras's theorem from horizontal and vertical displacement at a depth of 245 m is 0.015 m.



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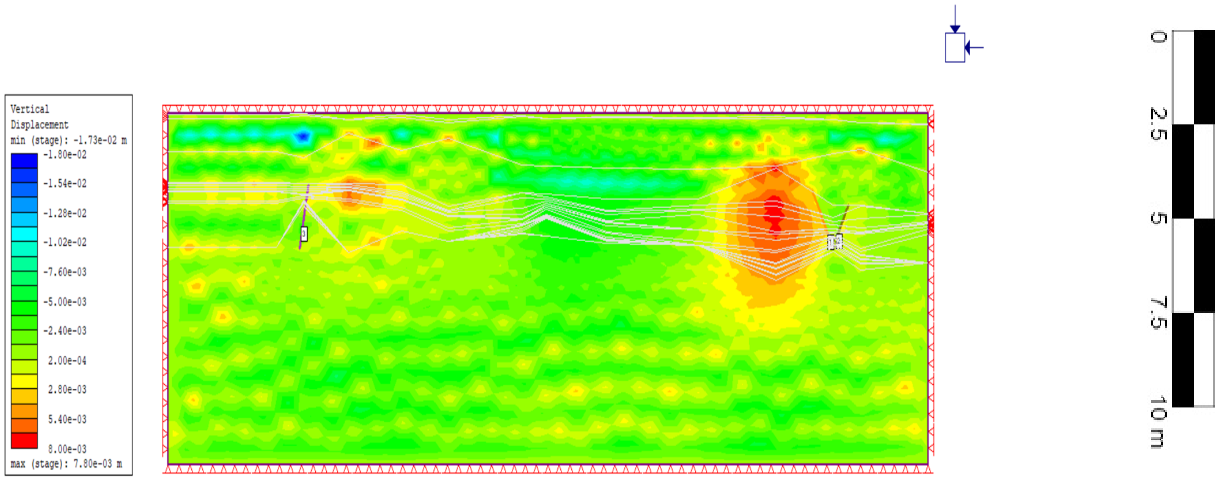

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Figure 7. (**a**) Spatio-temporal horizontal displacement based on only the X-component. (**b**) Spatio-temporal vertical displacement using only the Y-component (scale bar 1:55.38).

The seam convergence is the displacement in meters due to the vertical stress and is affected directly due to the caving of the formation. The boundary element method (BEM) based on the nonlinear differential equation developed by Heasley and calibration results (Figure 8) shows the maximum seam convergence value of 0.045 m after the extraction process, signifying high seam convergence values surrounding the pillar areas due to the exploitation phase. The measurement of the cross-section of the gob area (height × width) is 3 × 120 m with pillars of 3 × 112 m area [32].

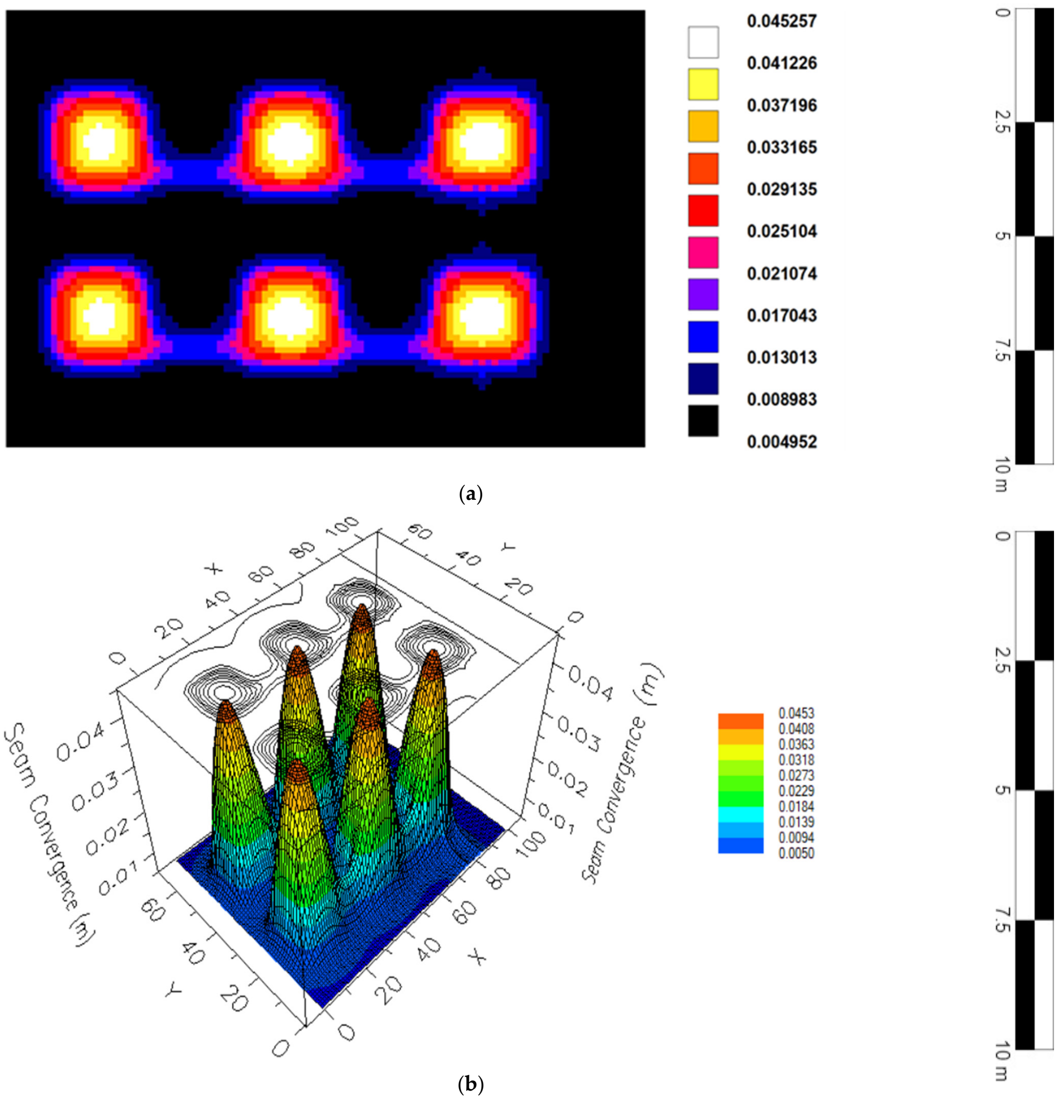


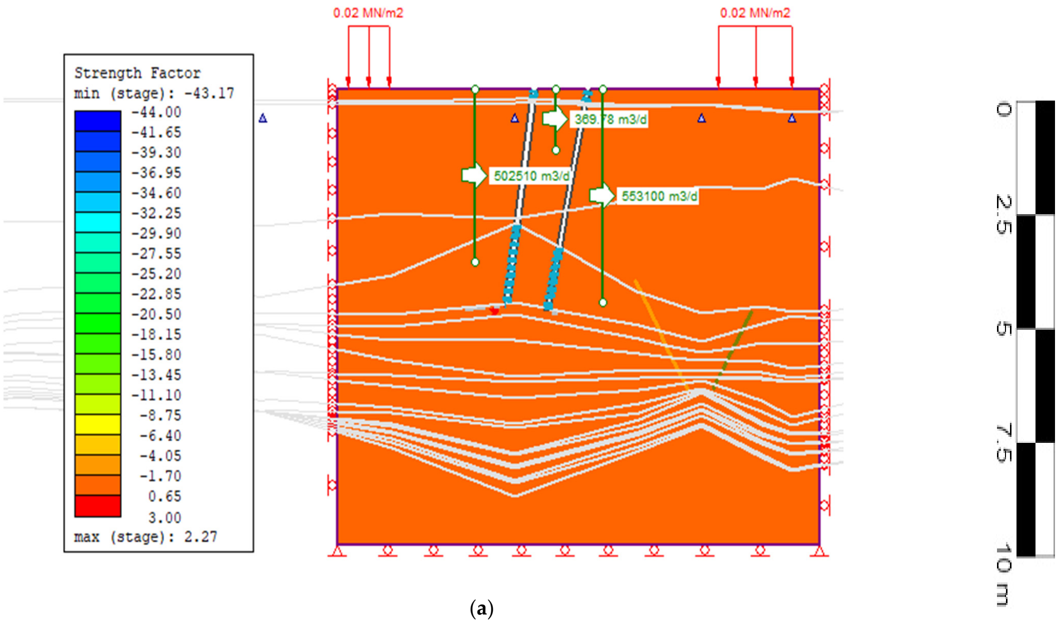
Figure 8. (**a**) Seam convergence of coal seam 1 in the square plot using a nonlinear partial differential equation. (**b**) Seam convergence of coal seam 1 in the 3D fishnet plot using regression analysis (scale bar 7:1).

The seam convergence at a depth of 245 m changed significantly from 0.015 m to 0.045 m with a 200% shift from the initial condition. The higher convergence value indicates the potential for hazards and major subsidence due to the extraction of the longwall panels [33,34]. The result suggests that the gob is at the maximum in the center of the panels, reduces gradually toward the unmined zones, and shows substantial displacements in the pillar zones [35]. The seam convergence values of this case study also correspond to the boundary element method analysis of the Barapukuria coal mine [36].

4.3. Factors of Safety

The factor of safety is a method to determine the stability of pillars [37]. In this case, the factor of safety values are predicted after each stage of the mine construction phases, considering transient groundwater conditions using finite element method (FEM) to clearly distinguish the effects of excavation on the whole construction area using Mohr–Coulomb failure criteria. Moreover, to further verify the results, the boundary element method (BEM) is applied, which uses logistic regression and log-normal distribution to avoid a negative factor of safety value, incorporating the Mark Beiniawki pillar strength equation [22,38].

In Figure 9a, the strength factor values of the recovery phase are compared with the second tunnel phase. The mean safety factor value of 0.9 for the recovery phase relative to tunnel 2 at depth 245 m is interpreted. The factor of safety results of the mine development in different critical stages as main shafts and tunnels also depicts consistency. This close observation suggests a catastrophic effect of the two major faults due to the construction of the main shafts. Hence, the construction of the main one appears to be the most challenging period, and the construction of the auxiliary shaft will be comparatively straightforward.



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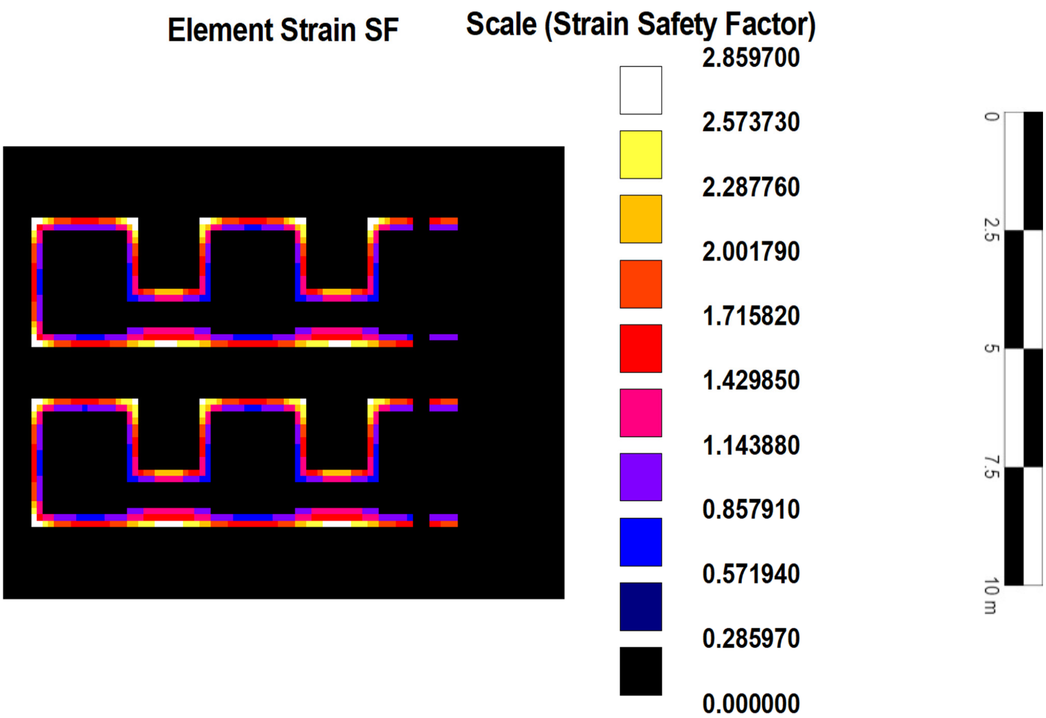

(**b**)

Figure 9. (**a**) Spatio-temporal strength factor of recovery stage relative to tunnel 2 using Mohr–Coulomb failure criteria (scale bar 1: 55.38). (**b**) The strain safety factor in the square plot using Mark Beiniawki pillar strength equation (scale bar 7:1).

Figure 9b presents the strain safety factor using the boundary element method (BEM), and the factor of safety values range from 0 to 2.85. For stable geometry of the formation, this model requires a safety factor value of 2.05, at which a 90% success rate is observed [34]. In the simulation, a safety factor value of 0.7 is observed near the longwall retreat at a depth of 245 m. However, shafts with artificial ground freezing techniques to increase strength and decrease water mobility, and tunnels with rock bolting rather than concrete or shotcrete, have been proven effective in the other local mines [2]. The tunnels in the regional mines with rock bolting reinforcements have shown very slight displacements and the shafts have remained stable, although ground attenuations are a common scenario in the mine's nearby areas.

Therefore, it is evident that there is a major chance of pillar failure in the central block of the Khalashpir coal basin, and it can be concluded that backfilling is compulsory for the construction of the Khalashpir coal mine. Hydraulic sand stowing can be an effective solution, since this process is adopted in many underground mines in similar settings worldwide [5].

5. Conclusions

The simultaneous application of the finite element method (FEM) and the boundary element method (BEM) can be a guarded approach to ensure the more likely forecasting of scenarios in which there is a shortage of seismic and rock mechanics data. In this study, the longwall panel's parameter, longwall unit designs, and geometry are specified logically depending on the feasibility study reports, borehole data, and regional geology. The primary concern for the Khalashpir coal exploitation will be the presence of aquifers well above the coal seams that will undoubtedly lead to less water inrush during the extraction period. The impacts of the major faults in the central block of the coal should be considered seriously. Coal extraction from the central part of the coal basin can eventually destroy the large coal basin due to major faults. The west and north-west block has an estimated reserve of 79.70 million tonnes, and no major faults are observed in this block. After investigating the impacts of slope stability constraints, the authors suggest initial extraction in the east and northeast blocks instead of the previously proposed central block. The statistical analysis of the FEM data sets that incorporate two discharge sections suggests a 96 percent accuracy of the model. Further simulation models should be developed that represent various supports and reinforcements at different stages, including novel code, especially through nonlinear partial differential equations to accurately evaluate local geological conditions and mine stability.

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