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 to understand 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 by boundary element method (BEM) that involves numerical discretization at reduced spatial dimension. Both results illustrate that there will be significant displacements in the formation, which infer subsidence and increases 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 & monitoring; geohazard susceptivity; numerical risk analyses; Vacuum Triaxial tests; Khalashpir Coal Basin

1. Introduction

Understanding the stress pattern, mine-induced stress redistribution, seam convergence, and strength parameters alteration is crucial for mine design, especially for the underground support system, panel, and pillar dimension design. A proper sequential design program from the initial mine entry development to the ending economic extraction stage can ensure a safe and efficient mining operation during the exploration period. Although empirical models developed from the field and laboratory-derived data are initially used for underground mine design, many numerical schemes incorporating measured mechanical properties have also been developed recently that can precisely investigate the mining situations under complex geological and boundary conditions [6]. 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, the impact of geological constraints, and the water on the overall mine stability during the mine development.

Khalashpir Coal Basin

The Khalashpir coalfield, one of five discovered coal fields 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 boreholes out of four drilled boreholes at depths ranging from 257.16 m to 484.15 m [20]. 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 boreholes data. 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 by thickness area method, proposes longwall mining method, and shaft locations [4,29]. Later, to validate the study of the venture, MPEMR collaborated with a local company IMC [21]. 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 [18]. 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 [10,22]. 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, faced major water inrush at the development stage, and the construction was abandoned for two years [25]. The average thickness of the DupiTila aquifer is 125 m in the Khalashpir coal basin which is high permeable (32.10–42.20 m/day), 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 [35]. 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 water inrush of the coal basin using boundary element numerical simulation technique and the results of which coverage to the initial stage settings discharge scenario of this research that estimates the discharge velocity using finite element method [24]. The Khalashpir coal basin is divided into five blocks. The blocks are the central block, east block, south block, north-east block, and west & north-west block with reserves of 136.28 mt, 40 mt, 28.33 mt, 17.39 mt 79.70 mt, respectively. Existing literature has 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 the 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 by common node point to one other, 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 [5].

2.1. Longwall Unit Specifications

Table 1 shows the parameters and specifications for finite element method analysis of the central block of the Khalashpir coal basin [19,28].

Table 1. Parameters and Specification for 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/m²

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.
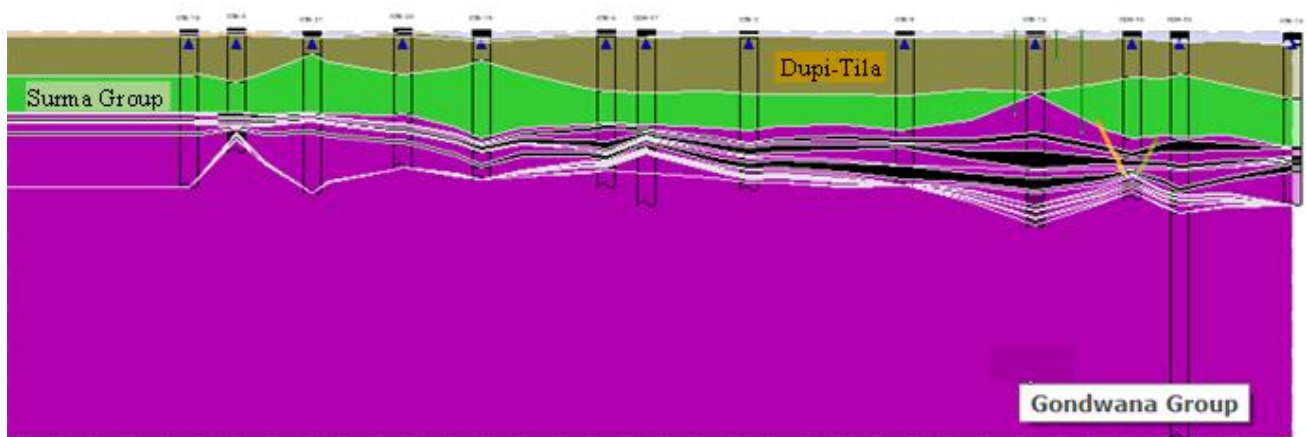

Figure 1. A cross-sectional view of the coal basin profile with 13 boreholes data where whitish ash, light orange, olive green, light green, violet, and black indicate Alluvium deposits, Madhupur Clay, DupiTila Formation, Surma Group, Gondwana Group, and Coal respectively.

Within study the area, the F1 and F6 joints (Figure 2) are located with a throw of more than 150 m and 100 m respectively with reference to the borehole of the GDH-46 [10].
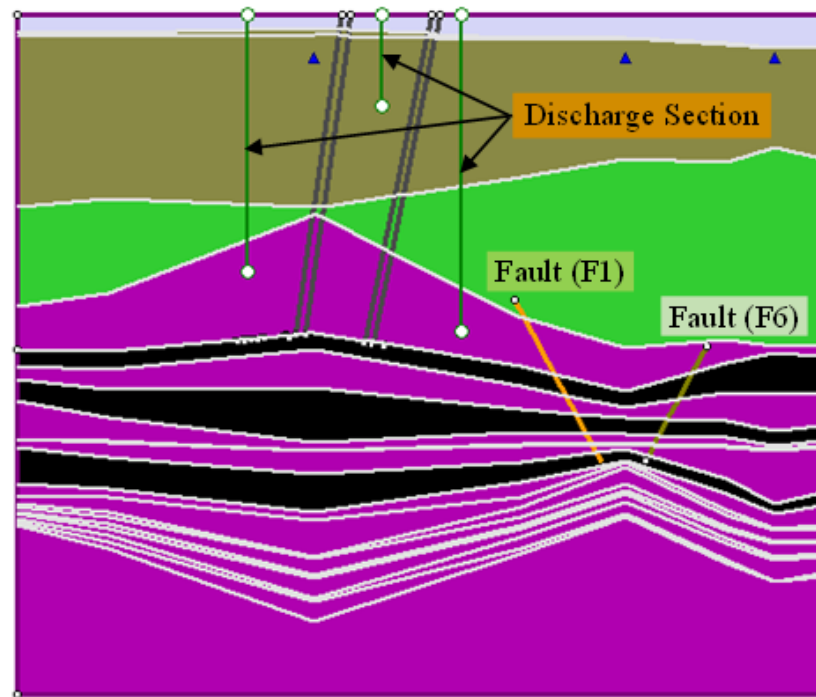
Figure 2. Cross-sectional geometry for the finite element method representing three discharge sections and faults over 50 hectares of land.

2.2. Stage Settings

This study involves the establishment of 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.

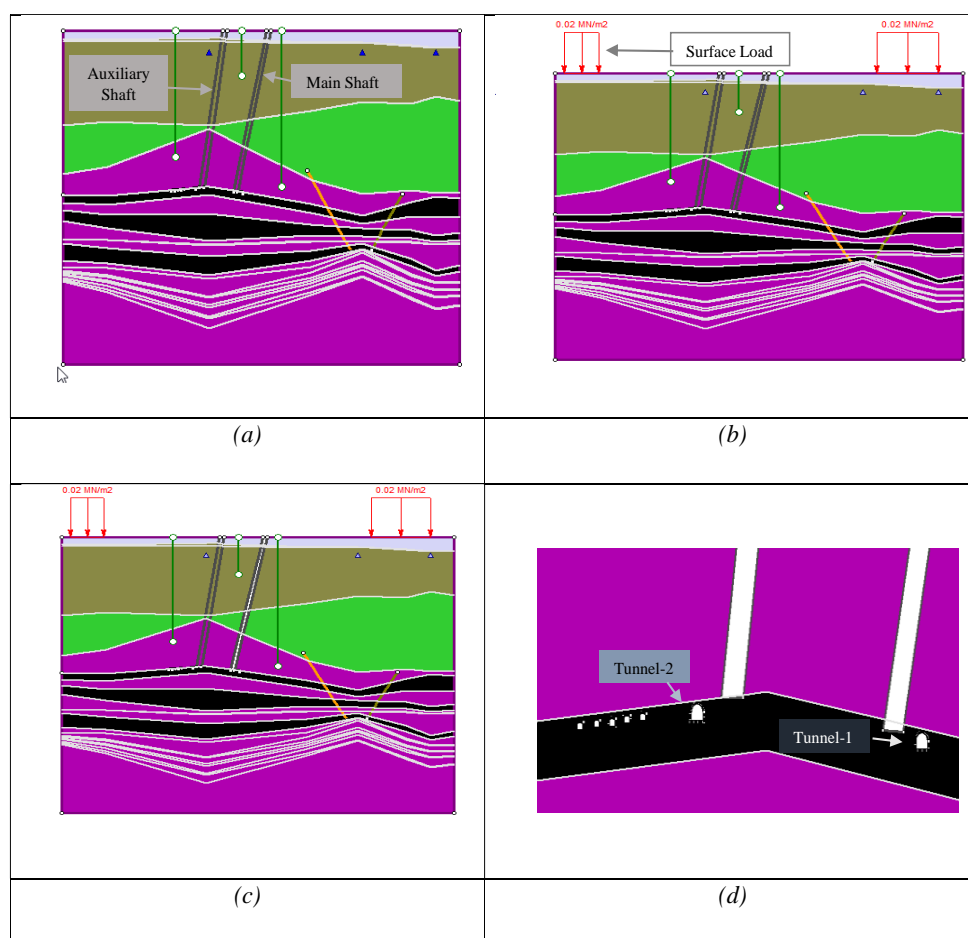| Name	Time (Days)	Drained?	PWP Method
Initial	0	Fully Drained	Steady State
Surface Load	160	Drained	Coupled
Main Shaft	710	Drained	Coupled
Auxiliary Shaft	1260	Drained	Coupled
Tunnel-1	1400	Drained	Coupled
Tunnel-2	1600	Drained	Coupled
Recovery	1650	Drained	Coupled

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/m² 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 5 panels construction.

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 [2]. The primary purpose of these rock mechanic properties is to identify and precisely predict the condition of the subsurface structure of the mine [28].

For each stratigraphic segment, the following properties are taken into account: unit weight, initial water condition, Poisson 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 ratio, Young's modulus, peak tensile strength, and cohesion are available from the tested borehole samples [4]. The fluid bulk modulus value is calculated using the elastic modulus and cohesion value [7]. The porosity value of Khalashpir Coal basin is predicted by correlating with the other Gondwana nearby coal basins considering the depth, groundwater conditions, fault locations, and other geotechnical parameters [33].

3. Boundary Element Method (BEM) Analysis

The boundary element method provides the numerical approximation of the boundary value problems by the solution of the boundary integral equation [1,3]. 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 [12–14]. Nevertheless, inhomogeneities of the rock mass, nonlinear governing differential equation, discontinuous boundary condition, possibilities of diverse boundary integral equation at the boundary, and pseudodifferential operators for resolving the Kernel's singularities of the integral equation may intensify the mathematical complexities in BEM [36].

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.

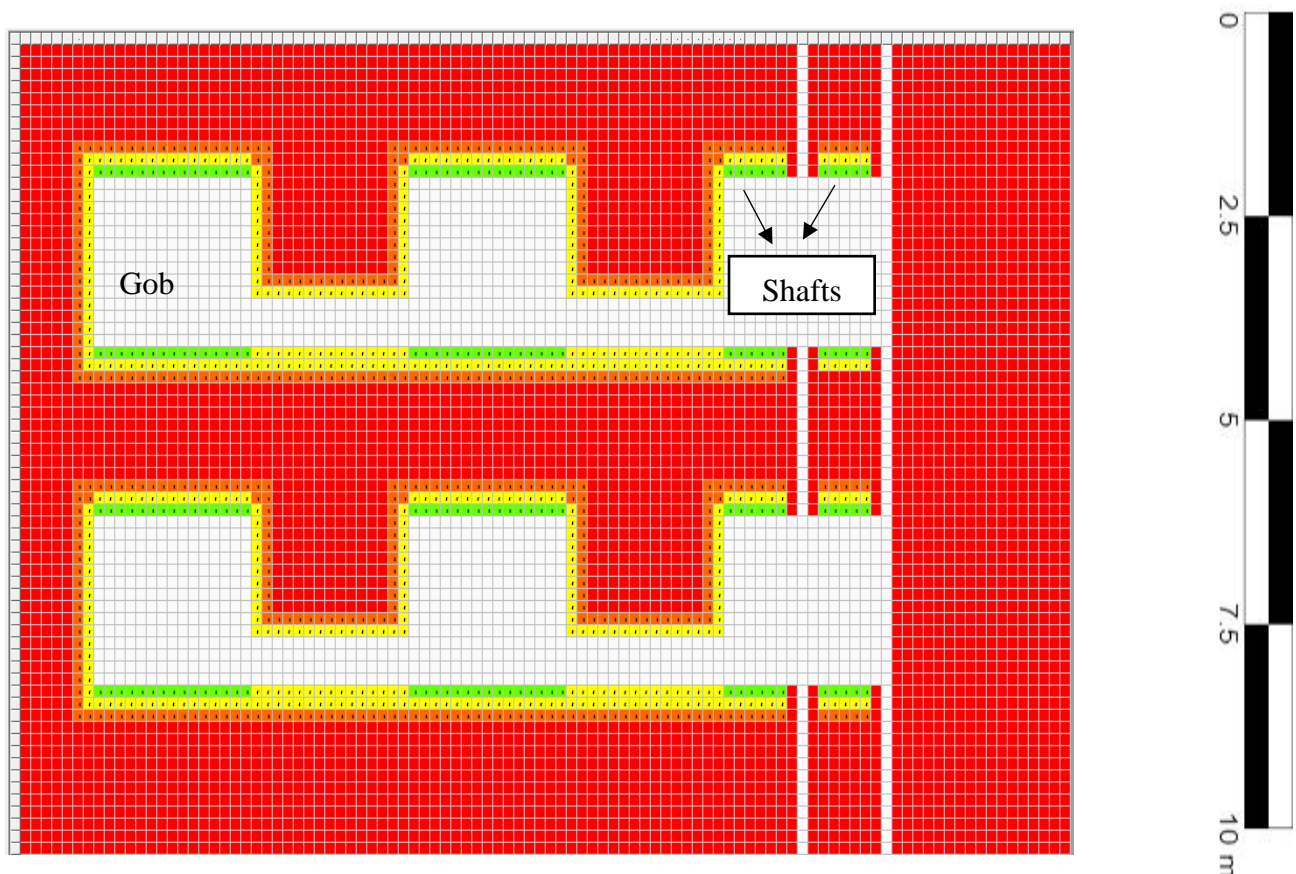| Parameters	Specifications
Main Shaft	Diameter of 8 m
Auxiliary Shaft	Diameter of 8 m
Extraction height	3 m.
Advance per shear	0.6 m (App.)
Longwall panels	120 m

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

The RMR value of 50 is employed for the Khalashpir coal basin based on the depth, 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 corresponds to 13,000 MPa [17]. The concept of lamination thickness is that the coal is interpreted in 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, the seam-I with a thickness of 10 m is considered 70 m in 70 grids along the y-axis. The coal is considered to exhibit elastic-plastic behavior, and the strain-hardening gob is the most appropriate fit for this case (Table 5) [38].

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 zone 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)	1,5919.53324777

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 Redistributions

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 [30,34]. 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 RS2 finite element package and total vertical stress by calibration of LaModel which 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 of 9.5 MPa at a depth of 245 m from the surface, denoting the longwall retreat's edge.
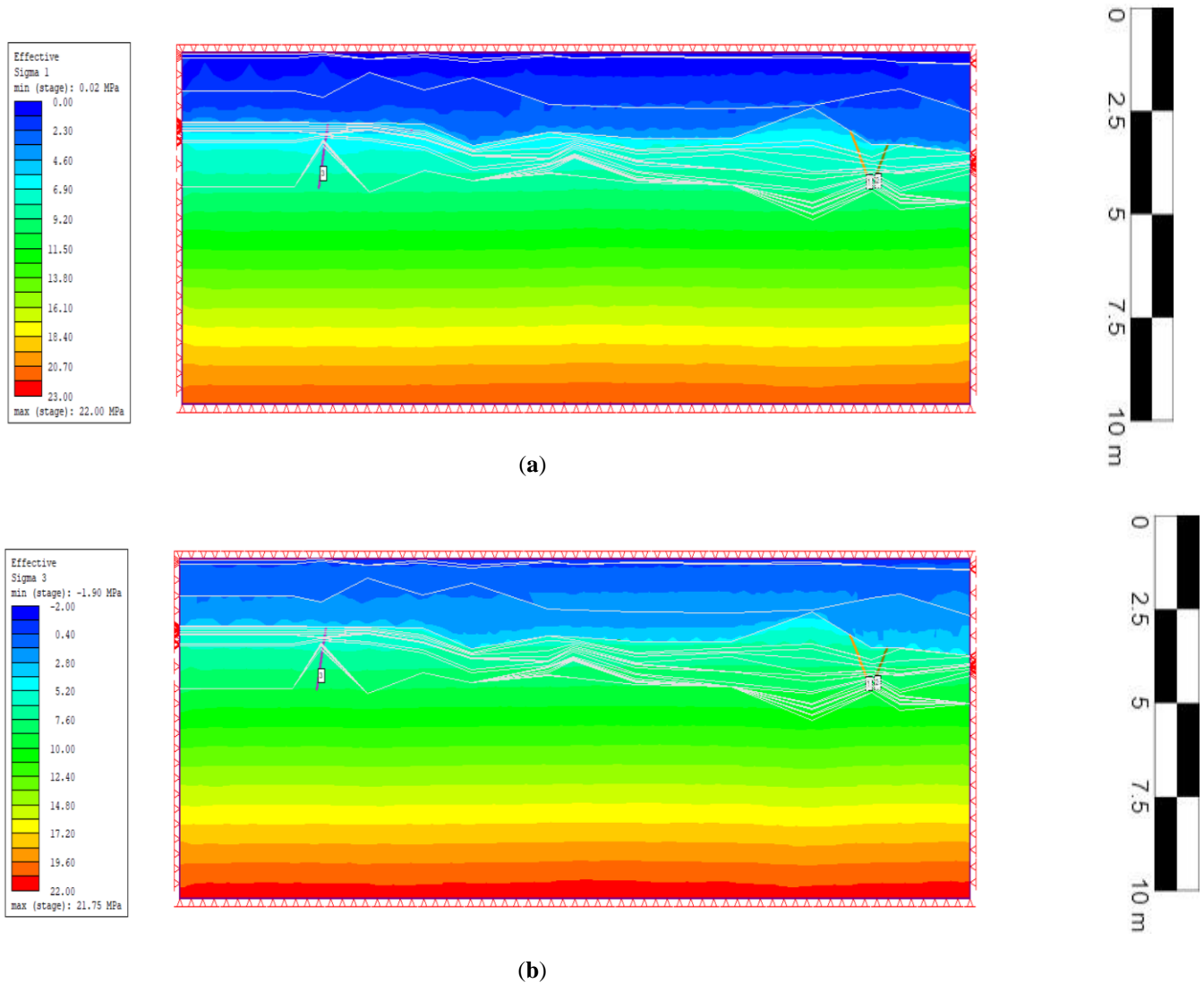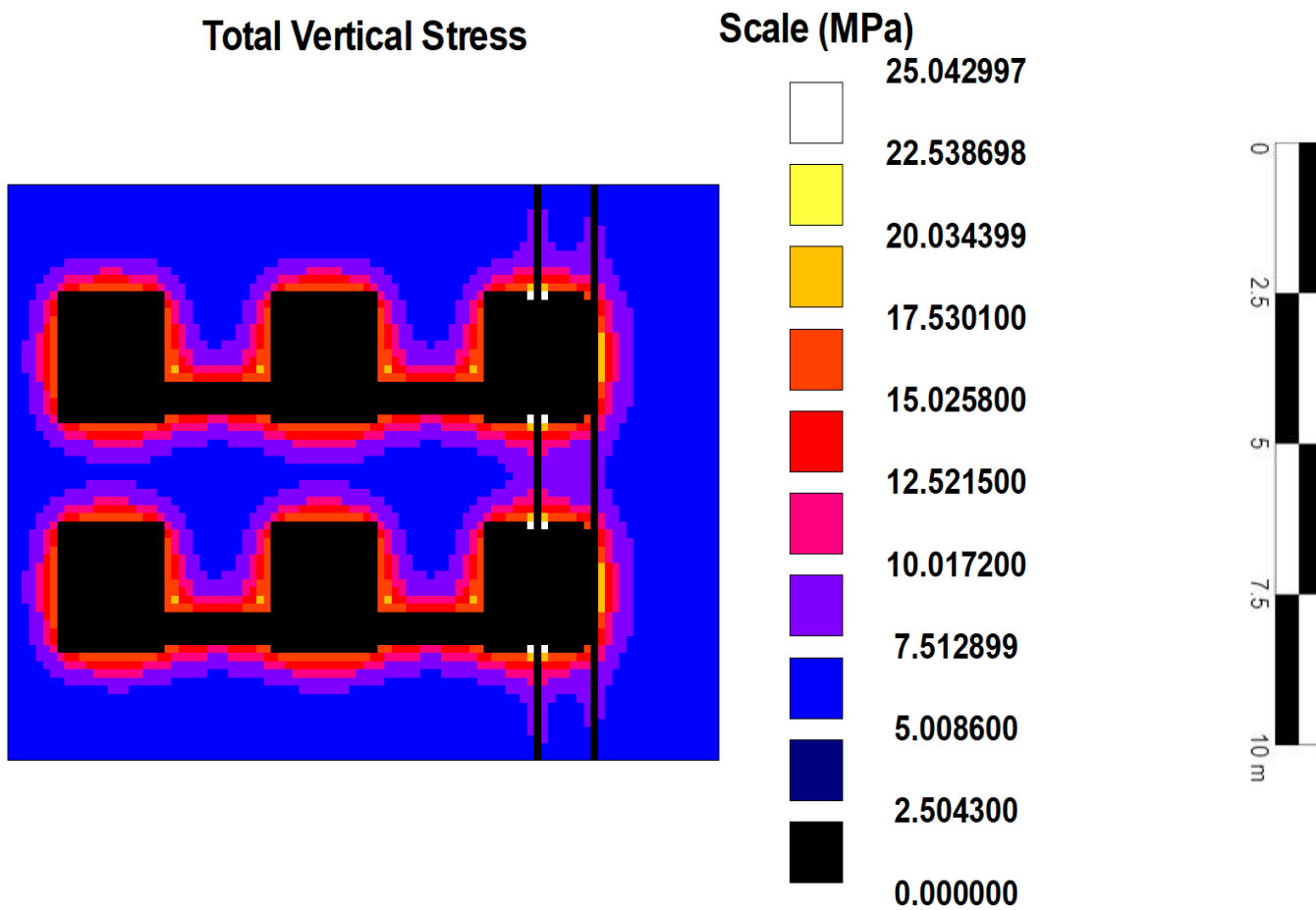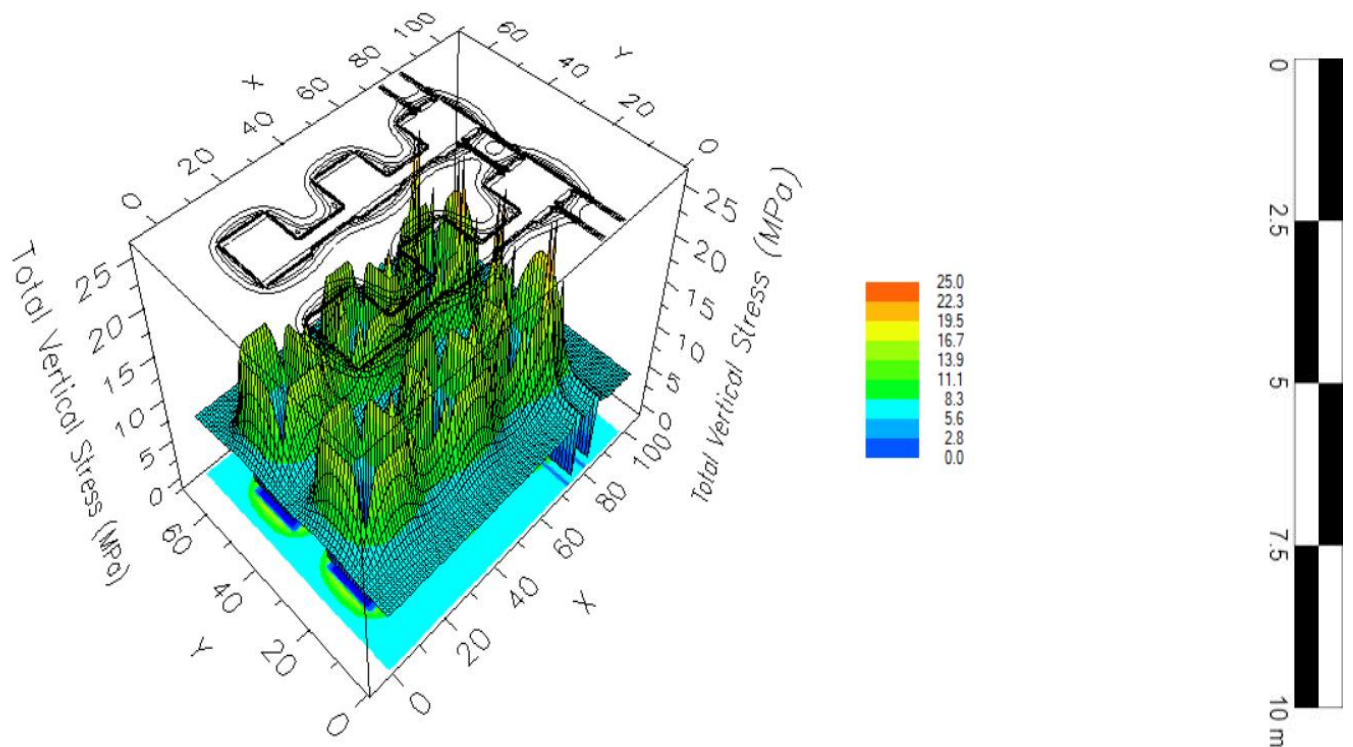

(**a**)

(**b**)

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 [32]. 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.

(**a**)

(**b**)

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).

The vertical stress due to the longwall retreat changes 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 agree with the stress distribution of the Barapukuria coal mine, which has similar geologic settings as the Khalashpir Coal Basin [25]. 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 consumes a 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 [27]. The movements of rock strata can be described as horizontal and vertical displacement that largely varies due to the magnitude of the modulus of elasticity [26].

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 moved 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.
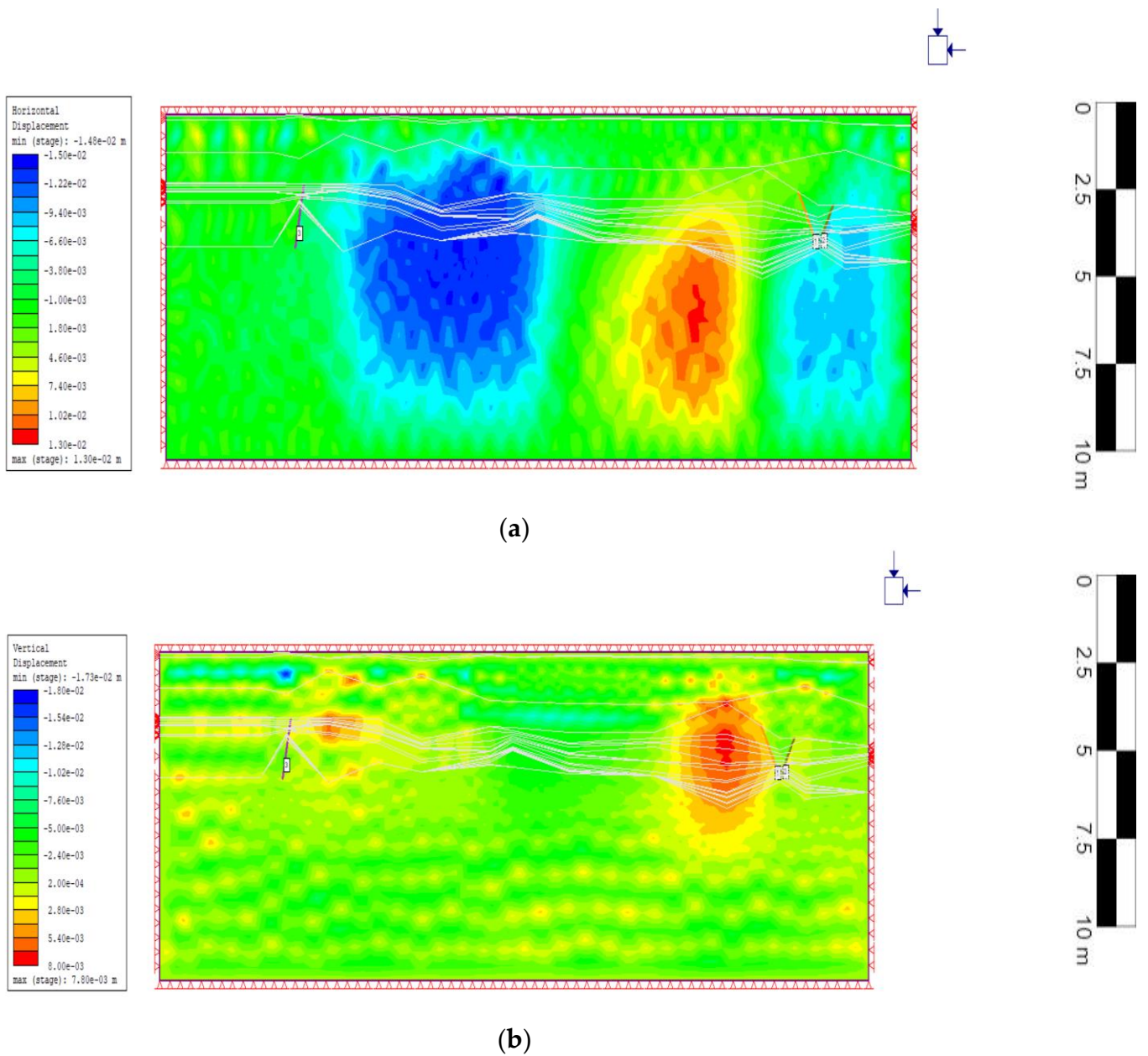
(**a**)

(**b**)

Figure 7. (**a**) Spatio-temporal horizontal displacement based on only X-component. (**b**) Spatio-temporal vertical displacement using only 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) show 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 [39].
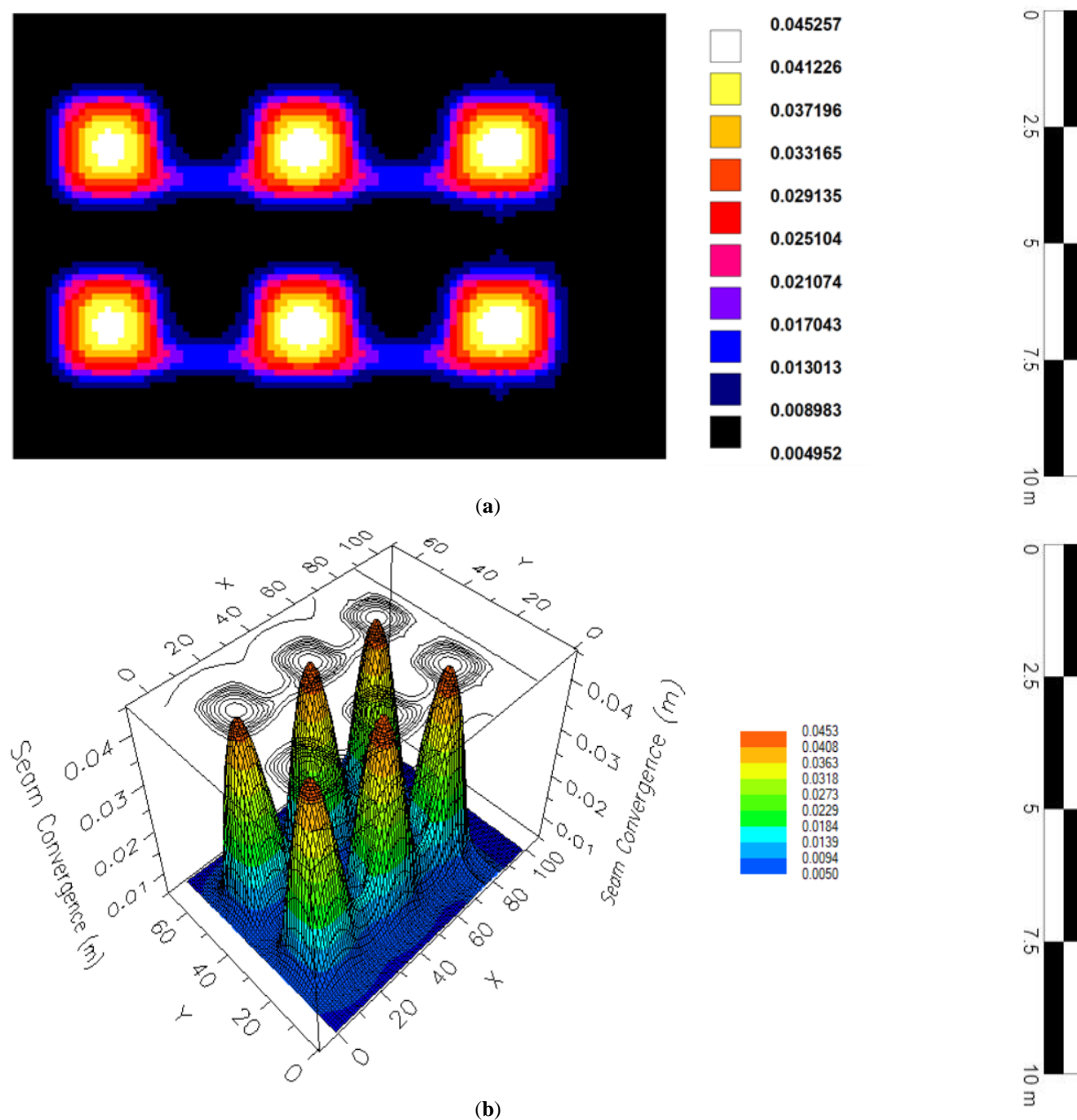
(a)

(b)

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).
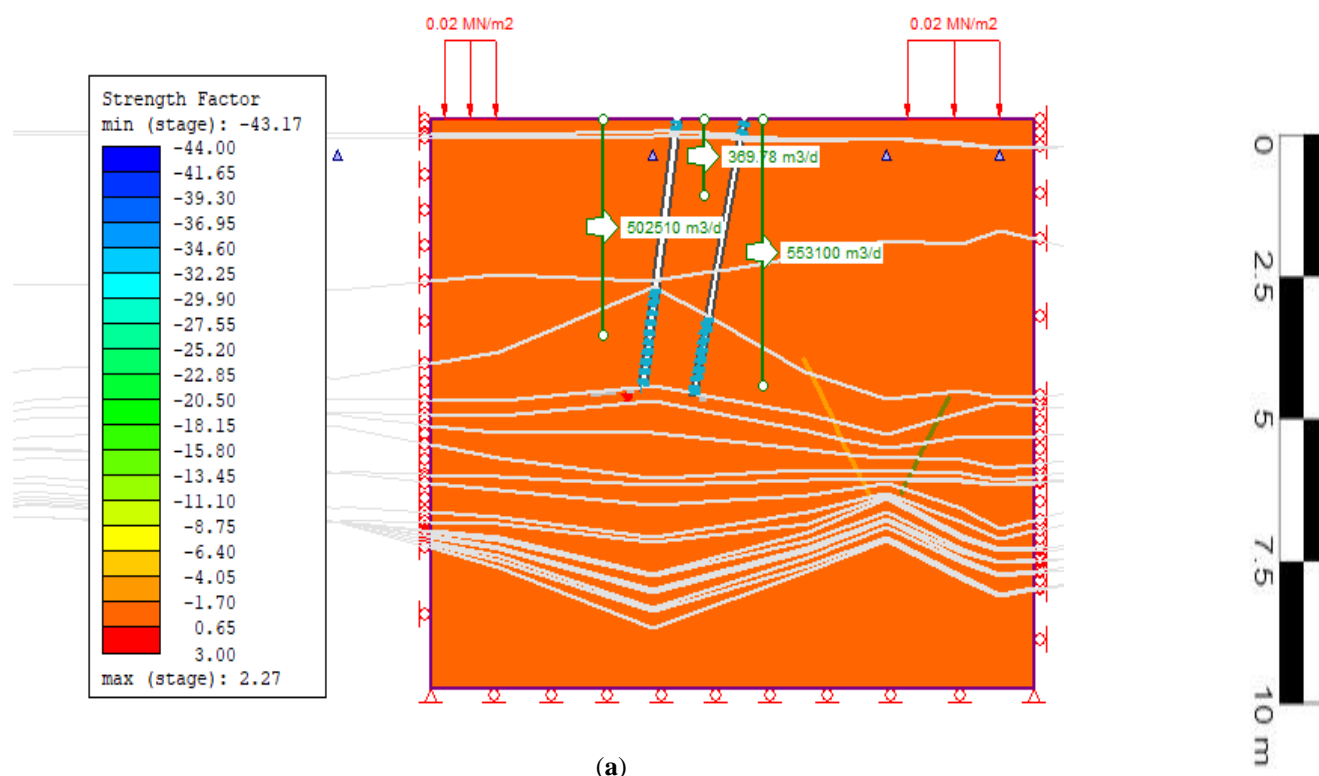
The seam convergence at depth 245 m changes significantly from 0.015 m to 0.045 m with a 200% shift from the initial condition. The higher convergence value indicates the potential for hazards and major subsidence due to the extraction of the longwall panels [15,16]. The result suggests that the gob is maximum at the center of the panels, reduces gradually toward the unmined zones, and shows substantial displacements in the pillar zones [31]. The seam convergence values of this case study also correspond to the boundary element method analysis of the Barapukuria coal mine [23].

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 is predicted after each stage of the mine construction phases considering transient groundwater conditions by finite element method (FEM) regarding each other 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 that uses logistic regression and log-normal distribution to avoid the negative factor of safety value incorporating Mark Beiniawki pillar strength equation [8,13].

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. The close observation suggests the catastrophic effect of the two major faults due to the construction of the main shafts. Hence, the construction of the main appears to be the most challenging period, and the construction of the auxiliary shaft will be comparatively straightforward.

Figure 9b presents the strain safety factor by boundary element method (BEM), and the factor of safety values range from 0–2.85. For a stable geometry of the formation, this model requires a safety factor value of 2.05, at which a 90% success rate is observed [11]. In the simulation, a safety factor value of 0.7 is observed near the longwall retreat at a depth of 245 m. However, the 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 [20]. The tunnels in the regional mines with rock bolting reinforcements show very slight displacements and the shafts remain stable although ground attenuations are a common scenario in the mine nearby areas.
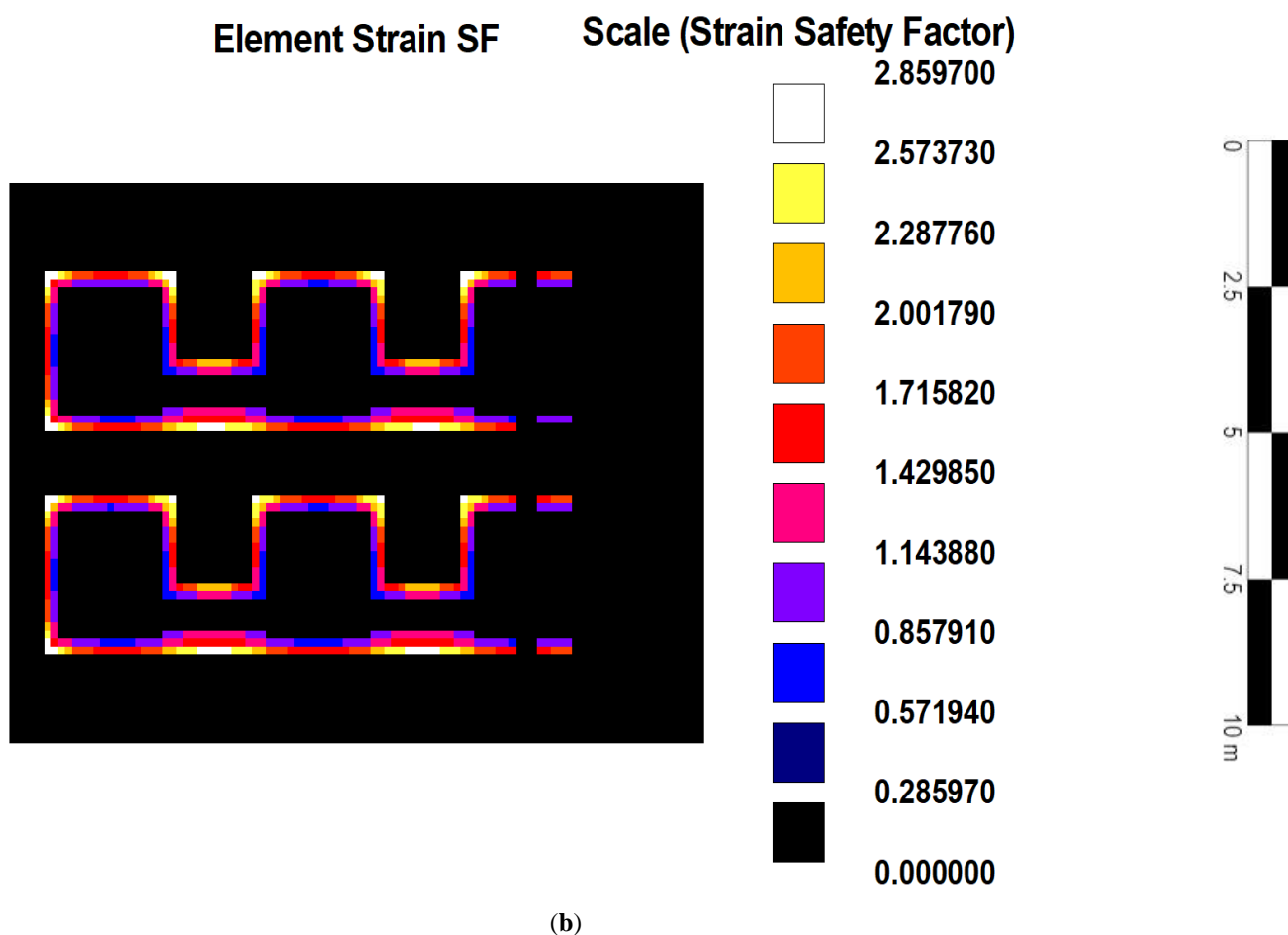

(**a**)

(**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).

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 of similar settings worldwide [21].

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, boreholes data, and regional geology the primacy 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 highly considered. Coal extraction from the central part of the coal basin can eventually destroy the large coal basin due to major faults. The west & 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 the initial extraction in the east & northeast blocks instead of the previously proposed central block. The statistical analysis of the FEM data sets that incorporate two discharge sections suggests 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 geologic conditions and mine stability.

Reference

1. Banerjee, P.K.; Watson, J.O. *Developments in Boundary Element Methods 4*; Elsevier Applied Science Publishers: London, UK; New York, NY, USA, 1986

2. Board, M.; Brummer, R.; Seldom, S. Use of numerical modeling for mine design and evaluation. In *Underground Mining Methods: Engineering Fundamentals and International Case Studies*; SME: Englewood, Colorado, 2001; pp. 483–491.

3. Brebbia, C.A. *Boundary Element Methods: Proceedings of the Third International Seminar, Irvine, California, July 1981*; Volume 3; Springer Science & Business Media: Berlin, Germany, 2013.

4. China Jinan Mining Development Corporation. *Techno-Economic Feasibility Study of Khalashpir Coal Mine Project, Dhaka, Bangladesh*; China Jinan Mining Development Corporation: Jinan, Shandong, 2006, *unpublished*.

5. Cook, R.D. *Concepts and Applications of Finite Element Analysis*; John Wiley & Sons: Hoboken, NJ, USA, 2007.

6. Del Greco, O.; Ferrero, A.M.; Oggeri, C. Experimental and analytical interpretation of the behaviour of laboratory tests on composite specimens. In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*; Pergamon Press: Oxford, UK, 1993; Volume 30, pp. 1539–1543.

7. Donaldson, E.C.; Alam, W.; Begum, N. *Hydraulic Fracturing Explained: Evaluation, Implementation, and Challenges*; Elsevier: Amsterdam, The Netherlands, 2014

8. Duncan, J.M. Factors of safety and reliability in geotechnical engineering. *J. Geotech. Geoenvironmental Eng.* **2000**, *126*, 307–316.

9. Farazi, A.H.; Quamruzzaman, C. Structural design of frozen ground works for shaft sinking by practicing artificial ground freezing (AGF) method in Khalashpir coal field. *Int. J. Eng. Sci.* **2013**, *2*, 69–74.

10. Hasan, M.N.; Arefin, K.M.S.; Uddin, M.K. *Report on the Seismic Reflection Survey in the Khalaspir Basin Area, Pirgong Upazila, Rangpur District*; Geolical Survey Report, Bangladesh; 1990, *unpublished*.

11. Heasley, K.A. *Numerical Modeling of Coal Mines with a Laminated Displacement-Discontinuity Code*; ProQuest LLC: Ann Arbor, MI, USA, 1999.

12. Heasley, K.A. A retrospective on LaModel (or Dr. Heasley's wild ride). In Proceedings of the 30th International Conference on Ground Control in Mining, Morgantown, WV, USA, 26–28 July 2011; pp. 26–28.

13. Heasley, K.A.; Agioustantis, Z.G. LaModel: A boundary-element program for coal mine design. In *Proceedings: New Technology for Ground Control in Multiple-Seam Mining*; Department of Health and Human Services: Washington, DC, USA, 2007

14. Heasley, K.A.; Barton, T.M. Coal mine subsidence prediction using a boundary-element program. In Proceedings of the Society for Mining, Metallurgy, and Exploration Annual Meeting, Orlando, FL, USA, 9–12 March 1998.

15. Heasley, K.A.; Sears, M.M.; Tulu, I.B.; Calderon-Arteaga, C.; Jimison, L. *Calibrating the LaModel Program for Deep Cover Pillar Retreat Coal Mining*; West Virginia University: Morgantown, WV, USA, 2009; pp. 47–57.

16. Heasley, K.A. Numerical Modeling of Coal Mines with a Laminated Displacement-Discontinuity Code. PhD dissertation, Colorado School of Mines, Golden, CO, USA, 1998

17. Hoek, E.; Diederichs, M.S. Empirical estimation of rock mass modulus. *Int. J. Rock Mech. Min. Sci.* **2006**, *43*, 203–215.

18. Hossain, H.Z.; Sultan-Ul-Islam, M.; Ahmed, S.S.; Hossain, I. Analysis of sedimentary facies and depositional environments of the Permian Gondwana sequence in borehole GDH-45, Khalaspir Basin, Bangladesh. *Geosci. J.* **2002**, *6*, 227–236.

19. Hustrulid, W.A.; Hustrulid, W.A.; Bullock, R.L. (Eds.) *Underground Mining Methods: Engineering Fundamentals and International Case Studies*; SME: Englewood, Colorado, 2001.

20. Imam, B. *Energy Resources of Bangladesh*; University Grants Commission of Bangladesh, Dhaka, Bangladesh, 2005; p. 277.

21. IMC. *Review of Techno-Economic Feasibility Study Khalashpir Coal Mine*; Government of the People's Republic of Bangladesh Energy and Mineral Resources Division Hydrocarbon Unit: 2009

22. Islam, M.N.; Uddin, M.N.; Resan, S.A.; Islam, M.S.; Ali, M.W. Geology of the Khalaspir Coal Basin, Pirganj, Rangpur, Bangladesh. *Rec. Geol. Surv. Bangladesh* **1992**, *6*, 809.

23. Islam, M.R.; Shinjo, R. Mining-induced fault reactivation associated with the main conveyor belt roadway and safety of the Barapukuria Coal Mine in Bangladesh: Constraints from BEM simulations. *Int. J. Coal Geol.* **2009**, *79*, 115–130.

24. Islam, M.R.; Faruque, M.O.; Adnan, S. Discharge Velocity and Drawdown of Groundwater Table Associated with UCG-Induced Cavity Zone: A Numerical Modeling Approach for the Khalashpir Coal Deposit, Northwest Bangladesh. *Electron. J. Geotech. Eng.* **2019**, 649–661.

25. Islam, M.R.; Hayashi, D.; Kamruzzaman, A.B.M. Finite element modeling of stress distributions and problems for multi-slice longwall mining in Bangladesh, with special reference to the Barapukuria coal mine. *Int. J. Coal Geol.* **2009**, *78*, 91–109.

26. Jeremic, M.L. *Strata Mechanics in Coal Mining*; CRC Press: Boca Raton, FL, USA, 2020.

27. Jia, D.; Zhou, Y.; He, X.; Xu, N.; Yang, Z.; Song, M. Vertical and horizontal displacements of a reservoir slope due to slope aging effect, rainfall, and reservoir water. *Geod. Geodyn.* **2021**, *12*, 266–278.

28. Kidybinski, A.; Babcock, C.O. Stress distribution and rock fracture zones in the roof of longwall face in a coal mine. *Rock Mech.* **1973**, *5*, 1–19.

29. Kil, Y.O. Khalashpir Coal Mine Project, Pirganj, Rangpur. Pumping Test Report of Exploration Boreholes on Khalashpir Coal Field. (unpublished).

30. Labuz, J.F.; Zang, A. Mohr–Coulomb Failure Criterion. In *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014*; Springer: Cham, Switzerland, 2012; pp. 227–231.

31. Li, Z.; Xu, Y.; Liu, H.; Zhai, X.; Zhao, S.; Yu, Z. Numerical analysis on the potential danger zone of compound hazard in gob under mining condition. *Process Saf. Environ. Prot.* **2021**, *147*, 1125–1134.

32. McCardle, B. An Assessment of Multiple Seam Mine Stress Conditions Using a Numerical Modelling Approach. The University of Queensland, Brisbane, QLD, Australia, 2016.

33. McKee, C.R.; Bumb, A.C.; Koenig, R.A. Stress-dependent permeability and porosity of coal and other geologic formations. *SPE Form. Eval.* **1988**, *3*, 81–91.

34. Menetrey, P.; Willam, K.J. Triaxial failure criterion for concrete and its generalization. *Struct. J.* **1995**, *92*, 311–318.

35. Miah, I.; Arifuzzaman, M. Interpretation of Subsurface Features on the Basis of Regional Gravity and Magnetic Data of Pirganj and its Adjoining Areas, Rangpur and Dinajpur District, Geolical Survey Report, Bangladesh, 1988, Unpublished.

36. Petersen, B.E. *Introduction to the Fourier Transform & Pseudo-Differential Operators*; Pitman Advanced Publishing Program: El-Bireh, Rashaya, 1983.

37. Reed, G.; Mctyer, K.; Frith, R. An assessment of coal pillar system stability criteria based on a mechanistic evaluation of the interaction between coal pillars and the overburden. *Int. J. Min. Sci. Technol.* **2017**, *27*, 9–15.

38. Sears, M.M. Calibrating the LaModel Program for Shallow Cover Multiple-Seam Mines. Ph.D. Thesis, West Virginia University, Morgantown, WV, USA, 2013.

39. Zhang, Y.; Wan, Z.; Li, F.; Zhou, C.; Zhang, B.; Guo, F.; Zhu, C. Stability of coal pillar in gob-side entry driving under unstable overlying strata and its coupling support control technique. *Int. J. Min. Sci. Technol.* **2013**, *23*, 193–199.