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Gateway stability analysis by global-local modeling approach

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ABSTRACT

Longwall mining is the most widely used mining method in underground coal mining. The stability of gateways is crucial for longwall mining as they provide many essential services such as transportation of excavated coal, ventilation of longwall face. High in situ stresses, mining induced stresses due to advancing longwall face, and poor rock mass quality leads to large deformation jeopardizing the stability of the gateway in Guobei coal mine. In this paper, the global-local modeling approach is used for analysing the stability of the gateway in the mine. In this approach, a mine scale 3D global model was constructed to extract the stresses acting on the gateway. The extracted stresses from global model were implemented into 2D local model of the gateway for detailed analysis. The used approach was verified by the field measurements taken from the modeled gateway. In an attempt to deal with large mine induced displacements, a support system composed of rock bolt, cable bolt and shotcrete was proposed. The verified model was used to evaluate the performance of proposed support system. It was concluded that the proposed support system can significantly reduce the displacements. The verified model facilitates the performance evolution of other alternative support systems considered by the mine management. The presented approach can be applicable for other deep underground coal mines, experiencing large gateway convergence.

1. Introduction

The most widely used mining method for underground coal mining is conventional retreat longwall mining due to high production rate and safety.[1] As any failure or collapse in the gateways may lead to interruption of the production and even loss of human life, there is a constant interest in the stability of the gateways in longwall mining.[2–7] Gateways are subjected not only to overburden stresses but also to mining induced stresses due to advancing longwall face. When such high stresses are combined with weak coal measure rocks, very large displacements are observed in the gateways of underground coal mines, especially in the deep environment. It is known that such large deformation requires rescaling and maintenance to keep the serviceability and the stability of gateway. Most of the cases the cost of the maintenance works becomes more costly than tunneling cost. Therefore, with the increasing depth, the need for reliable gateway stability analysis methods and approaches has been increasing.

For a reliable gateway stability analysis, the prediction of the mine induced stresses is essential. In situ tests, empirical, analytical and numerical modeling methods have been used for the prediction of in situ stresses, crucial parameter for design projects. In coal mining for the prediction of the stresses on pillar abutment in flat or slightly inclined coal seams some empirical, analytical methods and 2D numerical models are widely used.[8–15] In retreating longwall mining, gateways are allowed to collapse behind the retreating face. Therefore, the prediction of the stresses occurring around the intersection of longwall face and the gateway in front of the face is required. Moreover the stresses induced by advancing longwall face should be taken into account. For such circumstances, the use of 3D numerical modeling is inevitable for the prediction of the stresses required for reliable gateway stability analysis.[2,16–19] Other important component of the analysis is the assessment of rock mass properties. Due to the high cost of in situ tests rock mass properties are mostly predicted by using rock mass classification and characterization systems such as Q,[20] RMR[21] and GSI.[22] Among others, the GSI system has been increasingly used in recent years, due to the advantage of obtaining the complete set of rock mass strength and deformability properties or main design parameters. Originally the GSI system was used for hard rock characterization, then it was updated to cover weak rock mass.[23] After the update, the system has been widely used for the calculation of the design parameters of coal and coal measure rocks.[2,19,24–27] In this paper, GSI system was used for rock mass characterization and calculation of rock properties to be

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used in numerical modeling.

The purpose of this study is to present global-local modeling approach used for analysing the stability of the gateway. The approach was originally used for the prediction of the stresses in hard rock mine.[28,29] Recently, the approach has been used for coal mines for the prediction of the stresses on the gateway or pillars.[2] In this approach, as a first step mine scale 3D elastic global model is constructed to extract the stresses. In the second step, the extracted stresses are applied as boundary stresses to 2D elastoplastic local model of the gateway. The main advantages of the approach are high computational efficiency, due to the use of global scale elastic 3D model, and accuracy as a result of 2D elastoplastic local model of the gateway with high mesh density. The GSI values were directly assigned from field observations and core loggings following the suggestions,[30] intact rock properties such as m_i and uniaxial compressive strength (σ_{ci}) were determined in laboratory or using published sources as suggested by Hoek et al.[31] Having determined the GSI, m_i and σ_{ci} values a range of rock mass strength and deformability properties were calculated as suggested by Hoek et al.[31] and used in both global and local models. The induced displacements obtained from global-local modeling approach were compared with the field measurements to verify the approach used. The verified approach was used to propose a new support systems to reduce the induced displacements and keep them below the limit deformation specified by the mine management.

2. Field and laboratory studies

In Guobei underground coal mine, the overall quality of coal is quite poor due to complicated tectonic movements. The quality of coal mass is further reduced by induced stresses due to retreating longwall face. In China, almost 70% of coal mines use rock bolts as the main support element.[32,33] Similar trend is also observed in Guobei mine, rock bolts and grouted cable bolts are the main support elements. Large mining induced displacements due to retreating longwall face endangers the stability and the serviceability in the gateways of the mine.

Guobei underground mine is located in Huabai Coalfield in East China. In the mine, the immediate roof is 2.45 m thick mudstone and the main roof is 23.50 m thick sandstone. The immediate and main floors are 2.75 m thick mudstone and 14.7 m thick mudstone with fine sandstone intrusion, respectively. The stratigraphic column showing lithology of immediate, main roof and floor of the gateway in the mine is given in Fig. 1. The current depth of the mine is 650 m. The thickness and the dip angle of the coal seam are 6.5 m and 22°, respectively. In the Guobei mine, conventional retreat longwall mining method has been used. The location of the panels, modeled gateway and measurement stations are shown in Fig. 2. The main support elements used in 600 m long gateways are 2.4 m long grouted rebar bolts and 6.4 m long cable bolts, in some cases where large displacement is observed 15 cm thick shotcrete with 30 MPa 28 days strength is also applied. In the 8104 gateway, two measurement stations were constructed, station A and station B. Station A was located in the middle of the panel and station B was located at the end of the panel.

2.1. Rock mass and material properties

In this study, the geological strength index (GSI) is used to characterise various lithological units. The average GSI values for the immediate roof, main roof, coal, immediate floor and main floor are presented in Table 1 together with intact rock properties such as m_i constant and uniaxial compressive strength (σ_{ci}). The strength and deformability parameters were calculated using the suggested equations by Hoek et al.[31]

In order to calculate the rock mass deformation modulus (E_{mass}), GSI based empirical equations are widely used. In the latest version of the equation in addition to GSI value, intact rock Young's modulus (E_i) is also considered.[34]

Column	Lithology	Thickness (m)	RQD (%)	Remark
	Mudstone	2.15	30	
	Sandstone	23.5	50	Main roof
	Mudstone	2.45	15	Immediate .roof
	Coal	6.82	20	Coal with thinner dirt band
	Mudstone	2.75	10	Immediate floor
	Mudstone-Fine sandstone	14.7	40	Main floor

Fig. 1. Stratigraphic column showing the rock units.

$$E_{mass} = E_i\left(0.02 + \frac{1 - D/2}{1 + e^{((60+15D-GSI)/11)}}\right) \tag{1}$$

where, D, the disturbance factor, is assumed as zero. The calculated design parameters are shown in Table 1.

2.2. Instrumentation

Two measurement stations were constructed to measure the induced displacement occurring during the retreating 8104 longwall face. The distance between the measurement stations was equal to the half of the panel length, 300 m. Permanent pins were installed in the floor, roof and the sidewall of the gateway for the measurements. Wall to wall and floor to roof convergences were measured using the flexible tape. The induced displacement and convergences due to face advancements and the distance between the longwall face and the stations by the time of measurement were recorded (Fig. 3). For the first 200 m of face retreat, a very slight displacement change, less than 20% of total convergence was observed at station A. The displacements sharply increased when the distance between the face and station is around 50 m (Fig. 3). The final wall and floor to roof convergences for the station A are 611 and 481 mm, respectively. After 300 m of face retreat, station A was left behind the advancing face and caved with the hangingwall. Similar trend was observed for station B, less than 15% of the convergence occurred in 500 m face retreat, then a sudden increase in deformation was observed when the face distance closer than 50 m distance (Fig. 3). For station B, the maximum wall to wall and floor to roof convergence were 654 and 460 mm, respectively. For both stations, floor heave was significantly larger than roof sag due to relatively stronger immediate and main roof compared to rock unit at the floor. The wall to wall convergence is almost 1.5 times of the floor to roof convergence. This can be attributed by the fact that both sidewalls are composed of weak coal mass and the roof is composed of relatively strong roof strata.

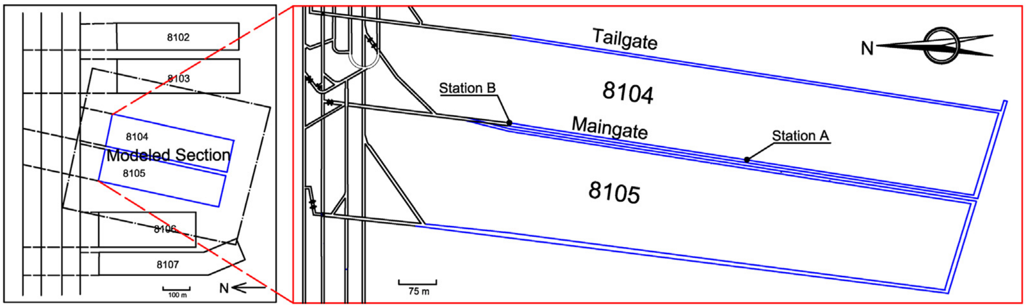

Fig. 2. Top view of the panels, roadway and measurement station locations.

3. Numerical modeling

For numerical analysis, both mine scale elastic 3D global and elastoplastic 2D local model of the gateway were constructed. From the global model stresses along gateway route were extracted and principle stresses were calculated to be applied as boundary stress to 2D local model.

In the preliminary design stage of many underground mining engineering structures such as underground tunnels, the stresses were predicted using empirical and analytical methods based on the depth. Whereas for longwall mining the stresses are variable in nature due to advancing face. For the prediction of the stresses on pillar abutment and ahead of or behind the face there are some empirical equations. Whittaker[12] investigated the vertical stress distribution around longwall panel and concluded that concentrated high vertical stress diminishes and backs to original virgin stress values by increasing distance from longwall face. Whittaker and Singh[13] proposed a nomograph showing normalized stress distribution around a longwall panel at moderate depth coal panel. Wilson[14] studied on the estimation of the stress around the longwall panel by utilizing cavity expansion theory; which assumes that the openings are excavated in cylindrical form in a homogenous, isotropic and elastoplastic medium.

For the prediction of the stresses, recently both elastic and elastoplastic 3D numerical modeling tools have been used rather than empirical methods. For capturing the deformation and convergences accurately for the considered gateway very fine mesh size is required. Such small element in a 3D elastoplastic model requires the use of massive elements leading to high computational power and long computational time. Whereas a 2D model with such finer elements can express the displacements, stresses around the gateway with reasonable computational power and time. Therefore, recently a global local modeling approach has been used to analyse the stability of the drift, such as footwall drift affected by excavation sequence.[2]

3.1. 3D Global model

For the prediction of the stresses on the roadway 3D elastic global model was constructed by FLAC 3D.[35] Geometrical properties of coal seam such as depth, inclination, thickness, panel width were same as the field shown in Fig. 2. Instead of all coal basin, only the selected part including the 8104 and 8105 panels, considered gateways and measurement stations used for verification were modeled. The model with dimensions is 807 m × 900 m × 900 m. The mesh size along the gateway route is as fine as 1 m and it increases with the increasing distance from the gateway. Overall view of the model is given in Fig. 4.

In the global model, only the elastic material properties were used as the purpose of this model is the extraction of the stresses rather than the observation of failed zones and deformation in the gateways. The main advantages of using elastic global model are computational efficiency allowing the conduction of a large number of analysis and parametric evaluations. In the global model very soft elastic material is used as goaf material. Kose and Cebi[36] suggested that the deformation modulus of the goaf material ranges from 15 to 3500 MPa. Whereas, based on the experiments Shabanimashcool and Li[37] suggested that the deformation modulus of caved material ranges from 60 to 100 MPa. Cheng et al.[3] and Jiang et al.[38] used a bit more stiff goaf material with a deformation modulus and Poisson's ratios of 190 MPa and 0.25, respectively. Some other researchers using single stage analysis using mine scale elastoplastic 3D model preferred the use of elasto plastic material properties for the goaf material for different purposes i.e. yielding pillar stability analysis.[39,40] The use of such material properties may change the level of the stresses well behind of the advancing longwall face. However, the purpose of this study is the extraction of the most critical stresses occurring in front of the advancing face. Moreover, according to the mine plan, the part of the gateway behind the longwall face will be caved together with the back of the panel. In this respect, it is reasonable to use the very soft material for analysing the stability of the gateway in front of the retreating longwall face. In this study the deformation modulus of 250 MPa and a Poisson s ration of 0.25 used as material properties for the goaf material.

As shown in Fig. 4, roller boundaries were used on the vertical and fixed boundaries were used at the bottom of the model. Whereas the ground surface was simulated as a free boundary. Virgin stresses were first initialized in the model using gravity, then the model was allowed to come to the equilibrium to consider the variations in density and stiffness of lithological units. Then panel excavation in the form of 50 m thick slices was simulated by replacing the material properties of the cut with very soft goaf material. In the model, it was assumed that

Table 1
Rock material and mass properties.

Rock unit	Rock material properties					Rock mass properties				
	m_i	Density, kg/m^3	σ_{ci}, MPa	Poisson's ratio, υ	E_i, GPa	GSI	c, MPa	ϕ, deg	σ_t, MPa	E_{mass}, GPa
Mudstone	6	2650	49.6	0.24	12.2	45	1.45	29	0.13	2.78
Sandstone	9	2690	85.8	0.22	18.6	67	3.45	42	0.79	12.5
Mudstone	9	2700	38.5	0.29	3.61	35	1.24	27	0.03	0.4
Coal	30	1420	7.0	0.39	5.0	30	0.98	24	0.15	0.50
Mudstone	15	2730	26.3	0.25	2.6	29	1.14	27	0.42	0.19
Mudstone with fine sand	4	2530	56.3	0.24	11.7	49	1.50	27	0.30	3.38

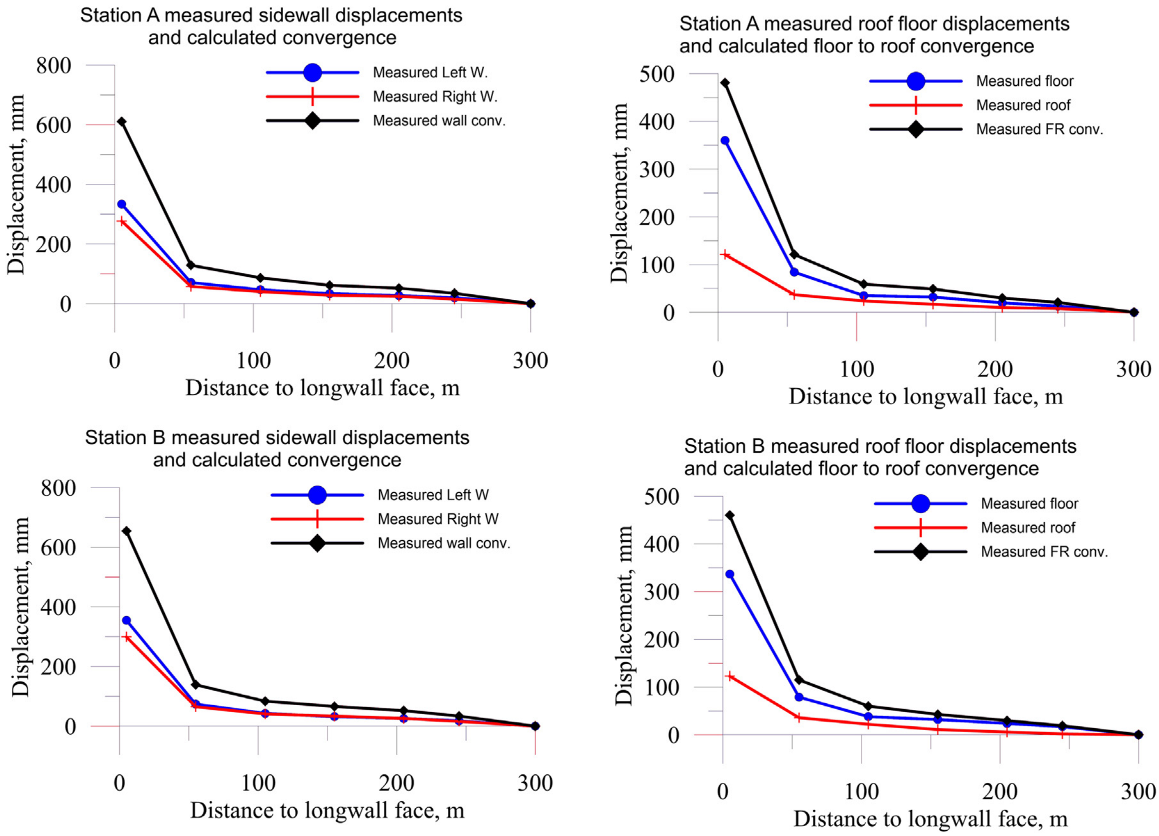

Fig. 3. Displacements and convergences at stations A and B.

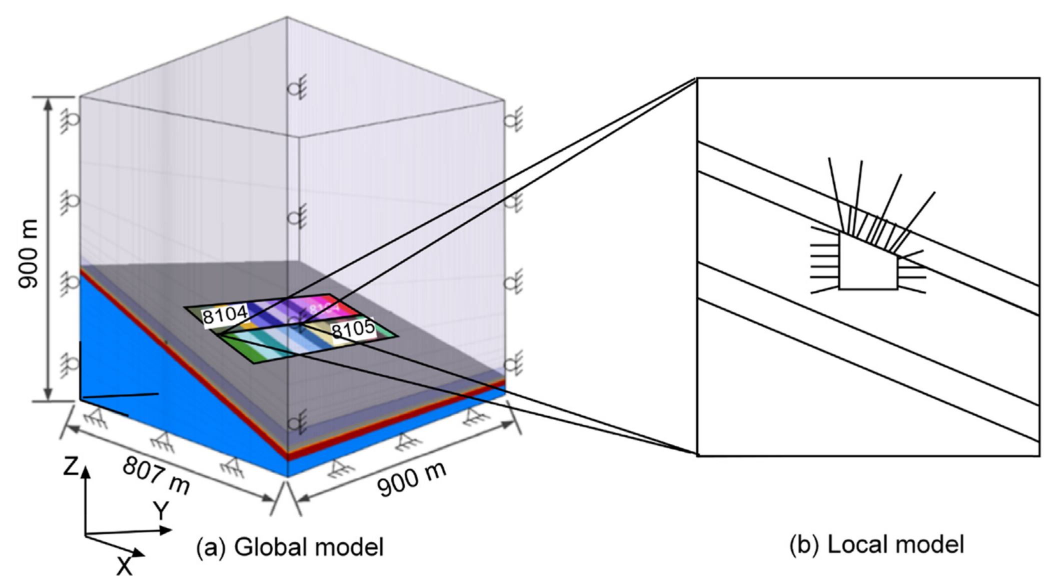

Fig. 4. Constructed global model geometry. (a) Global model; (b) local model.

600 m long panel will be produced in 12 cuts. It should be noted that 50 m long cut is compatible with the field measurement, going to be used for model verification. Single line aligned with the MM8104 maingate route was selected to extract the stresses (Fig. 5). Vertical stresses around the panel, following the excavations of Cut 4 and Cut 12 are shown in Fig. 6. Normal stresses changing depending on the excavation sequence are shown in Fig. 6. Vertical stress increases sharply as retreating longwall face comes closer to the measurement point and finally it reaches almost 1.5 times of insitu vertical stress.

As the extracted stresses will be used for designing for gateway support design, the normal and shear stresses were taken from the zones in front of the longwall face. The zones are also on stress monitoring lines along the position of gateway (Fig. 5). The extracted normal and shear stresses are used for the calculation of the principal stresses and their directions. The used 2D FE software, RS2,[41] requires the specification of the principle stresses and their directions i.e. angle from the horizontal for the maximum principle stress. As it can be understood from the provided orientation information in Table 2, σ_1 and σ_3 are in plane principle stresses normal to the roadway, whereas σ_2 is the out of plane stress in 2D local model.

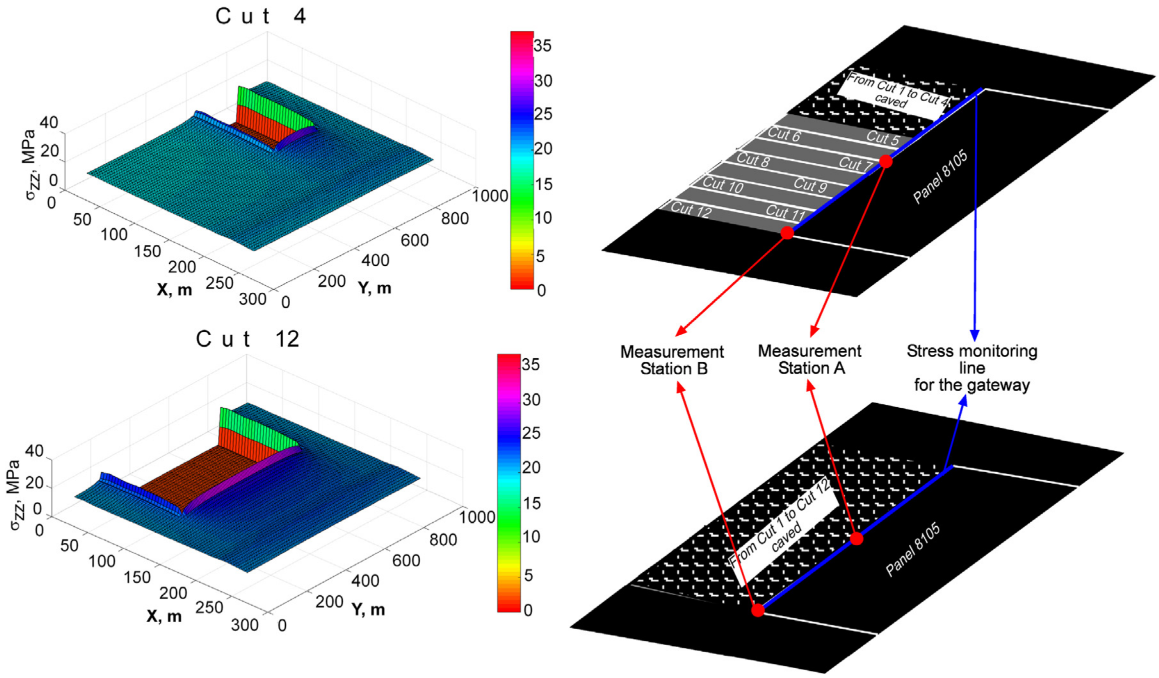

Fig. 5. Vertical stress distribution after Cut 4 and Cut 12.

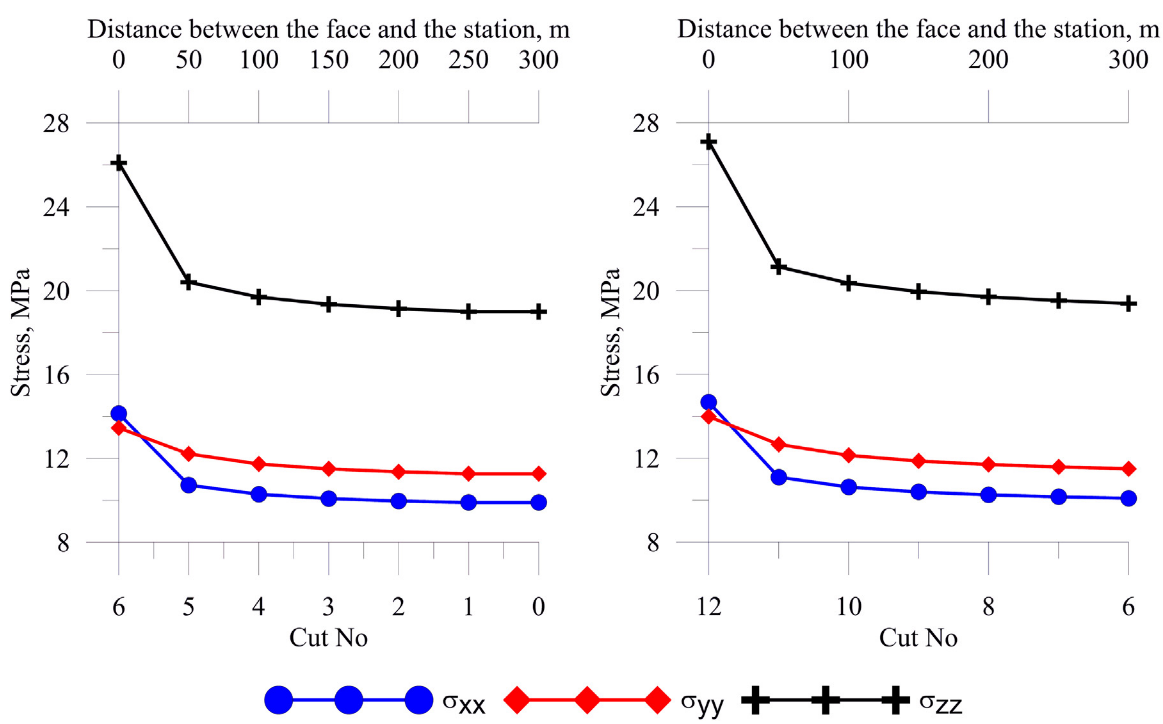

Fig. 6. Normal stresses on Station A and Station B during face retreat.

Using the normal and shear stresses taken from the global model, principal stresses and orientations were calculated (Table 2).

3.2. 2D numerical modeling of gateway

2D models were taken from a vertical X-Z plane of 3D global model at measurement stations A and B as shown in Fig. 4 and Fig. 5. A widely used 2D elastoplastic finite element software RS2[41] was used to model 8104 maingate. The constructed model allows the detailed stability analysis of the gateway. In the 2D local model, shown in Fig. 7, the minimum size of mesh close to the gateway boundary is around 5 cm, much finer than 3D global model allowing detailed deformation and stress analysis.

The calculated elastoplastic material properties presented in Table 1 were used in local model. In the paper elastic perfectly plastic with null dilatancy was used. The principal stresses presented in Table 2 were applied to outer model boundaries. The support pattern (Fig. 7) and properties (Table 3) are the same with those used in the field. The obtained deformations and corresponding distances for both stations A and B are shown in Fig. 8.

The relationships between the deformations and the distance between the station and longwall face were obtained from 2D model. For

Table 2
The magnitude and the orientations of the calculated principal stresses for station A.

Cut #	Stations	σ_1			σ_2			σ_3		
		MPa	α[a], deg	θ[b], deg	MPa	α, deg	θ, deg	MPa	α, deg	θ, deg
1	Station A	18.47	93	88	10.82	0	0	9.28	270	2
2		19.14	108	89	11.36	0	0	93.97	270	1
3		19.35	118	89	11.50	0	0	10.09	270	1
4		19.70	130	89	11.74	0	1	10.29	269	0
5		20.40	151	89	12.22	359	1	10.73	269	0
6		26.12	267	87	15.44	51	2	12.13	141	2
7	Station B	19.52	116	89	11.59	1	0	10.16	271	1
8		19.70	121	89	11.71	1	0	10.26	271	1
9		19.95	121	89	11.87	0	0	10.40	270	1
10		20.85	130	89	12.14	0	0	10.63	270	1
11		21.13	140	89	12.67	259	0	11.10	269	0
12		27.13	270	88	16.02	51	2	12.61	141	2

[a] Azimuth angle, clockwise from +Y axis.
[b] Dip angle below the horizon.

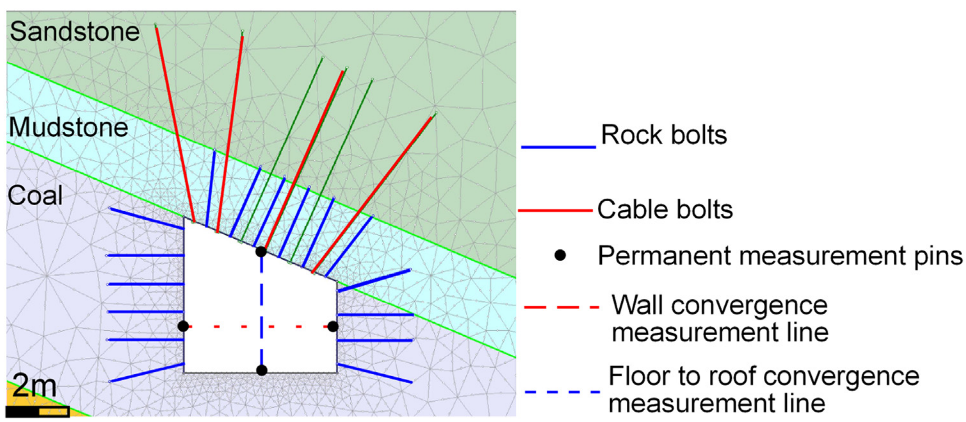

Fig. 7. 2D local model.

Table 3
Support properties.

Support materials	Tensile strength, MPa	E, GPa	Diameter, mm	Length, mm	Pre-tensioning, KN
Rock bolt	380	200	22	2400	80
Cable bolt	1670	195	17.8	6300	200

station A as the retreating longwall face approaches to the station, deformations increase gradually, for the last 50 m the erratic increase in displacements was observed (Fig. 9). The maximum deformations were 314, 370, 148, and 330 mm at the floor, left sidewall, top and the right sidewall, respectively. Similar trend is also observed for station B. In station B the recorded displacements were larger than station A as shown in Fig. 9. The maximum wall to wall and floor to roof convergences from the local model were 654 and 460 mm, respectively.

4. Verification of the used approach

In order to verify the used modeling approach, the displacements from 2D local model are compared with the field measurements. For stations A and B, the measured and predicted displacements and convergences together with the distance between measurement station and approaching longwall face are shown in Fig. 9, respectively. Dashed and solid lines show the measured displacements and convergences, whereas symbols show the predicted values. There is a good agreement between the measured and predicted convergences regarding to both magnitude i.e within 15% of the measured values and trend confirming that the used approach was reasonable and reliable.

4.1. Proposed support system and performance evaluation

In order to decrease the amount of mine induced sidewall and floor to roof convergences, a new support system was proposed. The verified 2D local model was modified and used for performance evaluation and stability of the gateway. In the modified model only support elements were changed, whereas rock properties and stress conditions were kept same with the verified local model. In order to reduce floor heave, similar to current trend observed in Chinese underground coal mines[27,42–45] additional support elements such as sidewall cable bolts, rock bolts and shotcrete in the gateway floor were added to the verified local model. The final version of the proposed support system is illustrated in Fig. 10. The properties of the proposed support elements are same with the existing support elements, given in Table 3.

The deformations and convergences from the field measurements and 2D model including proposed support elements were compared for stations A and B. As shown in Fig. 11, displacements and convergences were significantly reduced by the application of the proposed support system. For measurement station B where the largest induced deformations and convergences are observed, the percentage reduction of sidewall and floor to roof convergences are 86% and 4%, respectively.

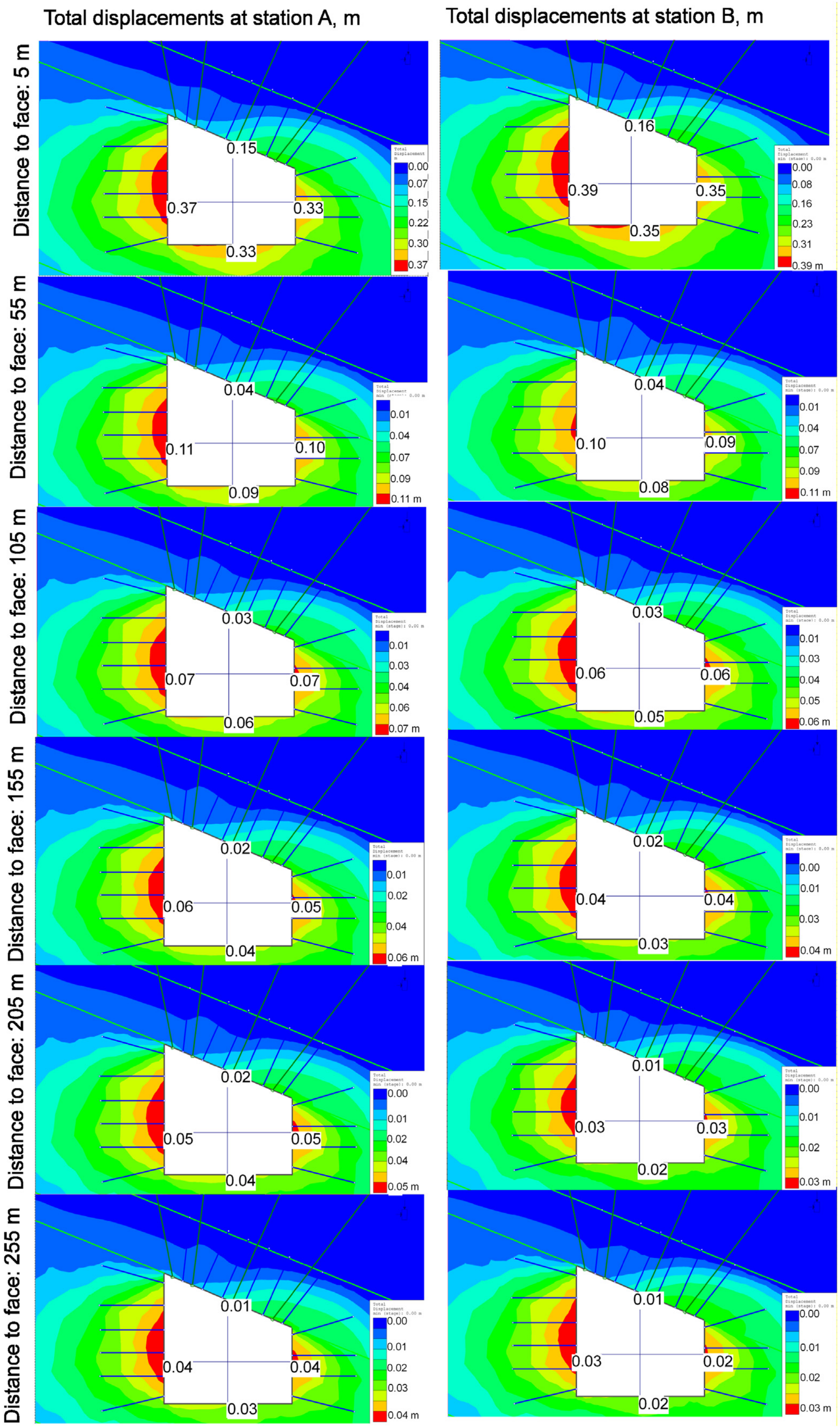

Fig. 8. Displacements and distances to face from 2D local model for Stations A and B.

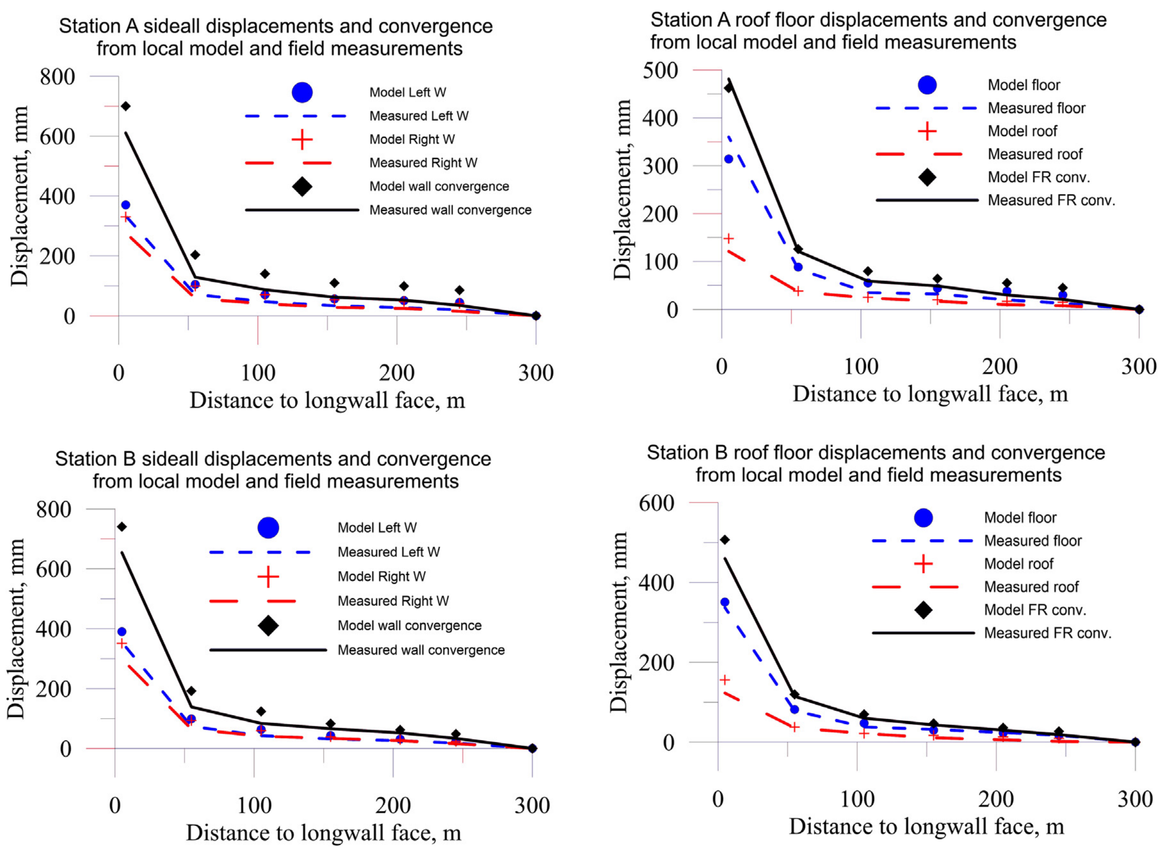

Fig. 9. Deformations and convergences from field measurements and local model for stations A and B.

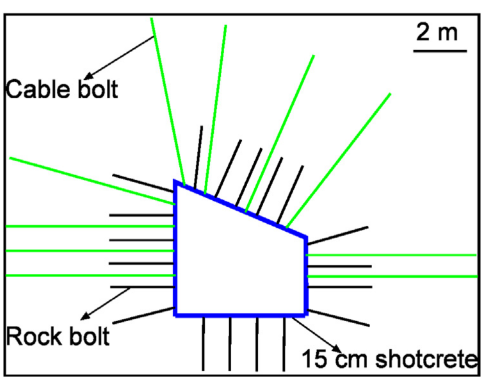

Fig. 10. Proposed support system to reduce gateway convergences.

5. Discussions and conclusions

In this paper, global-local modeling approach was implemented for the stability analysis of 8104 maingate. The extracted stresses were applied as boundary stresses to 2D local model.

When the predicted stresses are considered, the following conclusions are derived. The magnitude of the stresses increases considerably because of the advancing longwall face. For the considered gateway, the maximum principle stresses almost 1.5 times of insitu vertical stresses reaching up to 27 MPa. Based on the obtained normal and shear stresses from global model, the principal stresses and their orientations were calculated to be applied as outer boundary stresses in 2D local model.

Similar to field measurements, it was observed that stresses and thereby the induced displacements increased sharply when the longwall face gets closer than 50 m to measurement stations. In general, floor to roof convergence is lower than the sidewall convergences, due to relatively strong hangingwall. Moreover, left sidewall deforms a bit more than the right sidewall on the pillar side as results of principal stress orientation and supporting an effect of the pillar behind retreating longwall face.

In order to verify the presented approach displacements obtained from 2D local model were compared with the field measurement. The results proved that the used approach clearly captured the displacement behaviour of the roadway. Using the verified 2D model as a base, the performance of proposed support system to deal with large induced displacements was evaluated. It was noted that the proposed support system can significantly reduce the amount of induced displacements and therefore convergences. Using the results of this study, further stability and performance analysis can be made for different drift support elements and alternatives considered in Guobei mine. Moreover, the presented approach can be used for other coal mines dealing with large gateway convergences.

For future studies, more measurement stations at different production panels and gateways are suggested to monitor the performance of the proposed support system and to improve the proposed approach. The use of laser scanner is also suggested for more accurate displacement data and deformed roadway profile.

Acknowledgments

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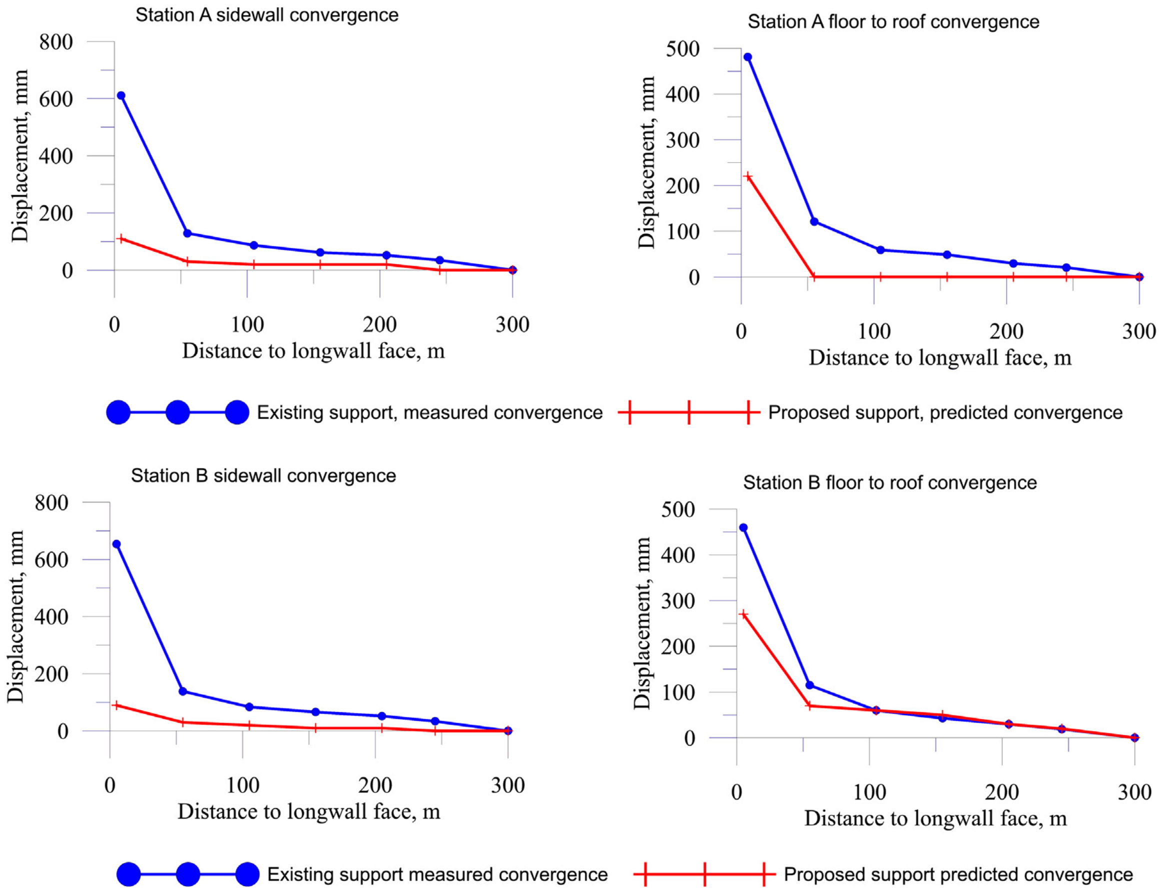

Fig. 11. Deformations and convergences from field measurements and the new 2D model of the gateway supported by the proposed support elements.

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