

Numerical Investigation of the Dynamic Mechanical State of a Coal Pillar During Longwall Mining Panel Extraction

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Abstract This study presents a numerical investigation on the dynamic mechanical state of a coal pillar and the assessment of the coal bump risk during extraction using the longwall mining method. The present research indicates that there is an intact core, even when the peak pillar strength has been exceeded under uniaxial compression. This central portion of the coal pillar plays a significant role in its loading capacity. In this study, the intact core of the coal pillar is defined as an elastic core. Based on the geological conditions of a typical longwall panel from the Tangshan coal mine in the City of Tangshan, China, a numerical fast Lagrangian analysis of continua in three dimensions (FLAC^{3D}) model was created to understand the relationship between the volume of the elastic core in a coal pillar and the vertical stress, which is considered to be an important precursor to the development of a coal bump. The numerical results suggest that, the wider the coal pillar, the greater the volume of the elastic core. Therefore, a coal pillar with large width may form a large elastic core as the panel is mined, and the vertical stress is expected to be greater in magnitude. Because of the high stresses and the associated stored elastic energy, the risk of coal bumps in a coal pillar with large width is greater than for a coal pillar with small width. The results of the model also predict that the peak abutment stress occurs near the intersection between the mining face and the roadways at a distance of 7.5 m from the mining face. It is revealed that the

bump-prone zones around the longwall panel are within 7–10 m ahead of the mining face and near the edge of the roadway during panel extraction.

Keywords Coal bump · Coal pillar · Elastic core · Longwall panel · Bump-prone zones · FLAC^{3D}

1 Introduction

Coal bumps have been a major safety concern in underground coal mines in China for more than 50 years. A coal bump refers to the sudden and violent structural failure of a coal seam that releases stored elastic energy and expels a large amount of coal and rock into a roadway or working face where men and machinery are present (Jiang et al. 2012; Mohamed 2003; Wang 2011). It can cause fatalities, injuries, and significant economic loss for the coal mining industry. Coal bumps occur more frequently in coal pillars, which are surrounded by previously mined coal seams or panels, than in other mining structures because of the high stresses. Therefore, study of coal bumps inside coal pillars is important to ensure coal mine safety and productivity.

Longwall mining is the preferred method when a high area extraction ratio is required and pillar mining is not possible (Brady and Brown 2006). Longwall mining can be used in both hard-rock and soft-rock coal mining environments and has been widely implemented by the Chinese coal industry with numerous modifications and improvements (Vakili and Hebblewhite 2010; Yasitli and Unver 2005). In longwall mining, the primary objective is to design coal pillars that are left in place to control mine stability and surface subsidence and, hence, to prevent damage to the surface or near-surface features, e.g., buildings, railways, highways, rivers, pipelines, etc.

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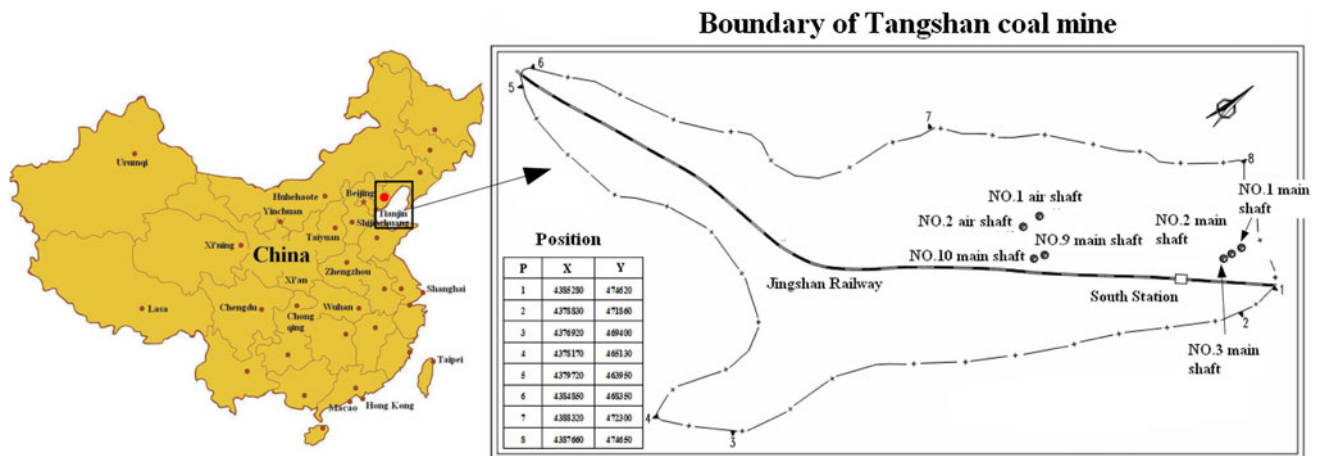
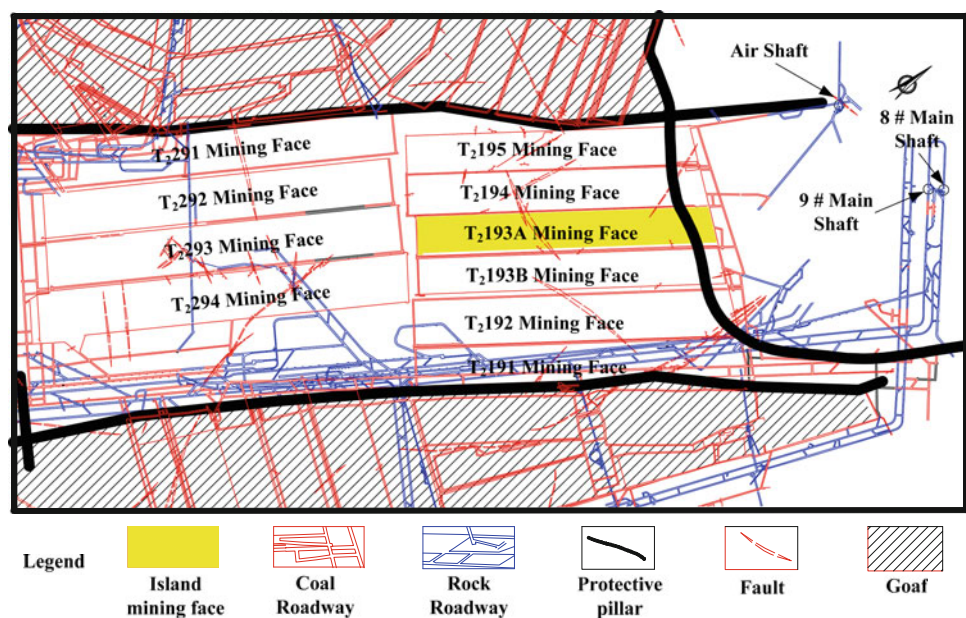


Fig. 1 Location of the Tangshan coal mine

Fig. 2 Layout of the T_{2193A} island mining panel



Numerous studies have been conducted to obtain comprehensive understanding of the proper design of a coal pillar. Several aspects of this research are discussed here. Coal pillar designs must take into account the mechanical and physical properties of the coal. In areas where coal extraction is mainly performed by bord-and-pillar mining, empirical data on the relationship between the strength and the size of the coal pillar is essential for the design. For this purpose, Bieniawski (1968, 1994) established an empirical relationship between the in situ strength of the coal and the size of the pillar. Medhurst and Brown (1998), in a comprehensive study to establish a framework for the in situ strength and deformation properties of coal pillars for a range of width-to-height ratios, investigated the effects of size on coal strength by performing a series of triaxial compression tests to provide engineers with a practical and systematic method for estimating the mechanical properties

of a coal seam. Coal pillar strength is fundamental to pillar design: Salamon (1967, 1970, 1998) proposed an empirical approach based on pillar width and height for pillar strength calculations in South African coal mines with a wide range of international applications. In the 1990s, a database of Australian coal pillars (Galvin et al. 1999; Galvin 2006) was analyzed, both by itself and in combination with the South African database used by Salamon and Munro. Based on this analysis, a similar empirical strength formula was proposed.

The relationship between coal pillar strength and deformation has always been a major concern in the pillar design process. To investigate the complete load–deformation behavior of coal pillars, a set of rectangular and square coal pillars was tested in situ by Wagner (1974, 1980). This research highlights the distribution of stress in a coal pillar and the importance of the coal in the pillar core

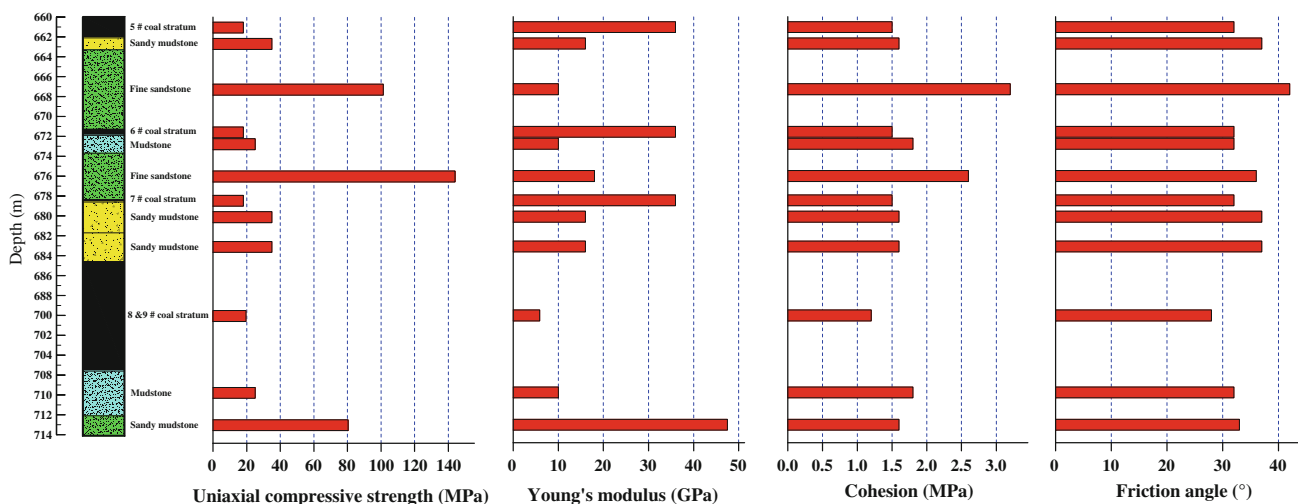
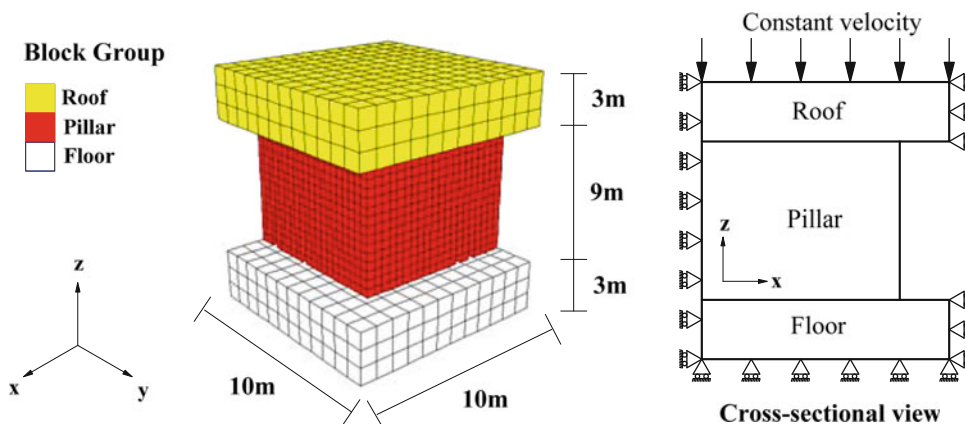


Fig. 3 Simplified panel stratigraphy and geotechnical parameters of the seam, roof, and floor strata

Fig. 4 Sketch of the FLAC^{3D} mesh and boundary conditions



that is stressed to yielding, which may remain structurally effective at peak strength. Additionally, Wagner identified that a coal pillar may still have an intact core even when the peak pillar strength has been exceeded and that the central portion of the coal pillar plays a significant role in its loading capacity.

Empirical and theoretical methods have both been developed to model the mechanical properties of a coal pillar, the relationship between the peak strength and the size of a coal pillar, and even the role of an intact core in the stability of a coal pillar. However, there is limited information currently available in the literature about the dynamic mechanical state of a coal pillar during the extraction of a longwall mining panel and prediction of coal bumps in the pillar. In this study, based on the geological condition of a typical longwall panel from the Tangshan coal mine in the City of Tangshan, China, a numerical fast Lagrangian analysis of continua in three dimensions (FLAC^{3D}) model was created to understand the dynamic mechanical state of a coal pillar during longwall panel extraction. In this study, the vertical stress is

considered to be an important precursor to the occurrence of a coal bump and is studied to examine the dynamical state of a coal pillar.

2 Longwall Mining Panel in the Tangshan Coal Mine

The Tangshan coal mine is located in Tangshan City, China (Fig. 1). It is well known for its large number of island longwall mining panels. The Tangshan coal mine district is 14.55 km long and 3.50 km wide. The mineable zones have total area of 54.60 km². There are eight mineable coal seams in the Tangshan coal mine. The T₂193_A panel selected for this study is 11 m thick and has dip angle of 9°. As shown in Fig. 2, both sides of this panel have been previously extracted, thus making it a typical island longwall panel where coal seam #9 was extracted. Protective coal pillars were left on both sides of the panel to ensure its stability (denoted by thick red lines in Fig. 2). The T₂193_A panel has an overburden depth of 700 m, being 860 m long in the strike direction and 124 m wide in

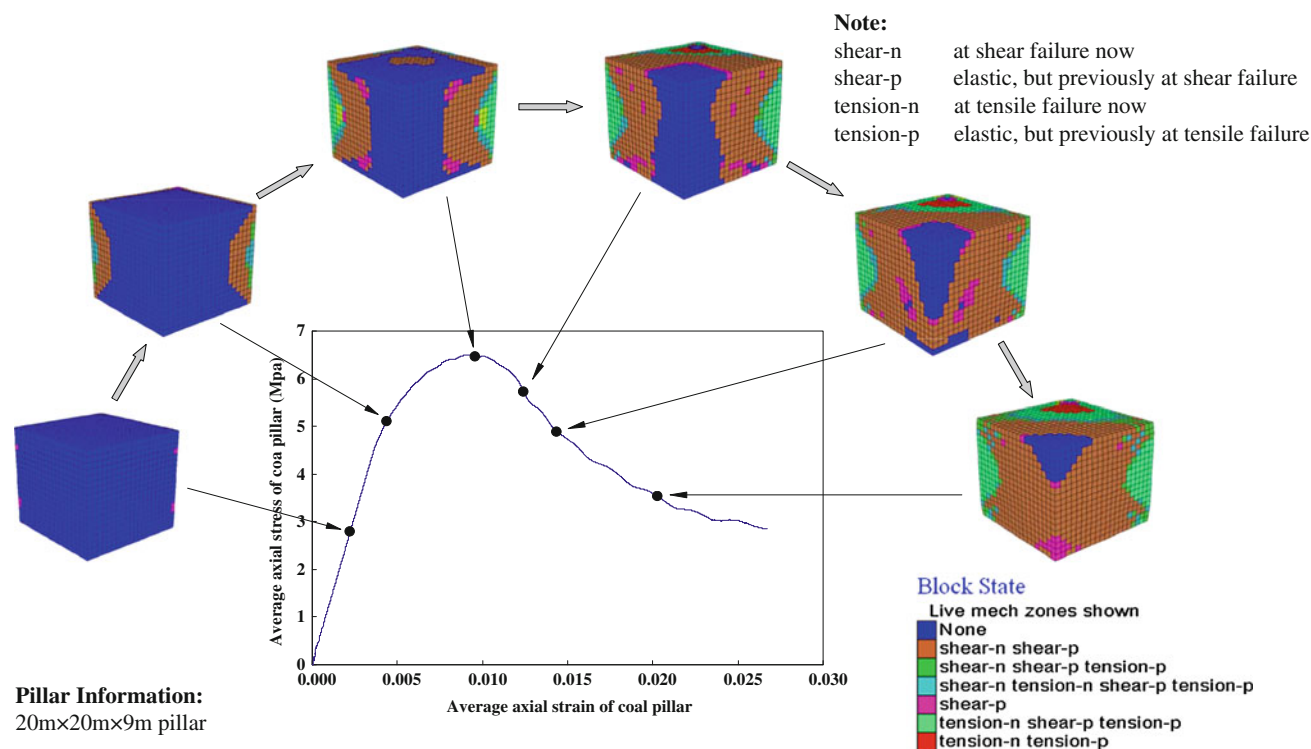


Fig. 5 Variation in the elastic core of a 9-m coal pillar under compressive loading

the dip direction. The panel is mined using the top coal caving mining method. The height and width of the panel ventilation and haulage roadway are 4.0 and 3.0 m, respectively. These two roadways employ a support system consisting of anchor–wire–shotcrete combined with a steel arched yielding frame. The length of the anchor is 2.4 m. The immediate roof of the panel is composed of sandy mudstone and has average thickness of 2.9 m. The main roof is dark-grey sandy mudstone with average thickness of 3.1 m. The immediate floor of the panel is composed of mudstone and is approximately 4.5 m thick. The main floor is composed of dark-grey sandy mudstone and is approximately 2.0 m thick.

It is crucial to properly assess the properties of the surrounding rock to obtain acceptable results for numerical modeling. Therefore, the physical and mechanical properties of each geological unit must be determined. In general, the properties of the surrounding rock are determined by laboratory testing. Samples of the surrounding rock described above were obtained from exploration drilling cores and rock blocks taken directly from the Tangshan coal mine. According to the available literature (Brady and Brown 2006), the uniaxial compressive strength, Young's modulus, Poisson's ratio, cohesion, and friction angle of the rock are needed to analyze the mechanical state of the coal pillar for use in this study. Uniaxial compression tests were used to determine the uniaxial compressive strength, Young's modulus, and Poisson's ratio. The cohesion and

friction angle of the surrounding rocks were obtained by triaxial compression tests. Based on the results of these tests, the panel stratigraphy and other important geotechnical parameters of the coal seam, roof, and floor strata are shown in Fig. 3.

3 Elastic Core in Coal Pillars

In his work, Wagner (1974, 1980) highlights the progressive failure of a coal pillar from the pillar boundary back towards the center. His work identified that a coal pillar may have an intact core, despite the peak pillar strength being exceeded. In his research, Wagner indicated that the central portion of a coal pillar plays a significant role in its loading capacity. In this study, the intact core of a coal pillar is defined as an elastic core.

To further investigate the mechanical state of the elastic core, FLAC^{3D} was employed to create a model of a coal pillar with dimensions of $20 \times 20 \times 9 \text{ m}^3$. In this study, the coal pillar is modeled using quarter-symmetry analysis (Wang 2011a, b). Figure 4 shows an example of the FLAC^{3D} mesh over one-quarter of the pillar, as well as the roof and the floor modeled in this study. The pillar element dimensions are constant at $0.5 \times 0.5 \times 0.5 \text{ m}^3$, whereas the thickness of the roof and the floor are chosen to be 3 m for the numerical model. A constant velocity is applied to the top of the model in the negative z -direction to generate vertical loading on the pillar. The velocity magnitude is set

Fig. 6 Sketch of the FLAC^{3D} mesh for the T₂193_A panel

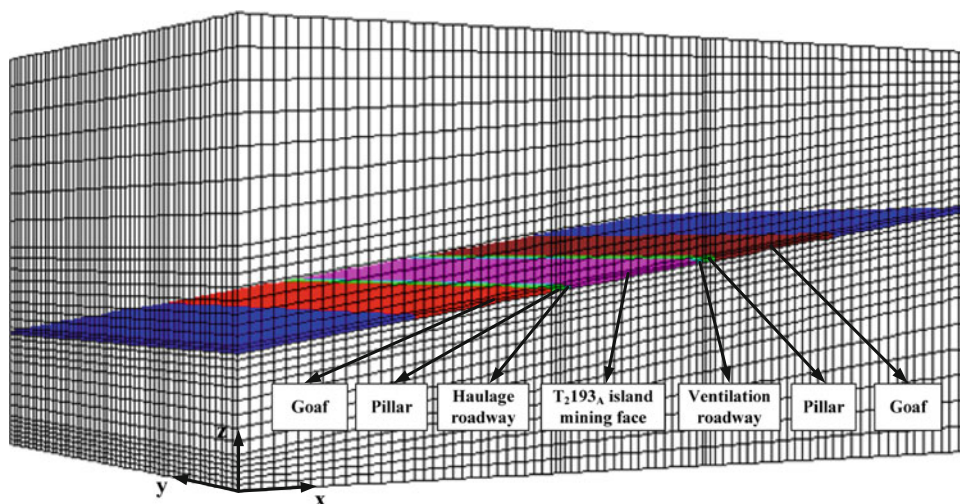
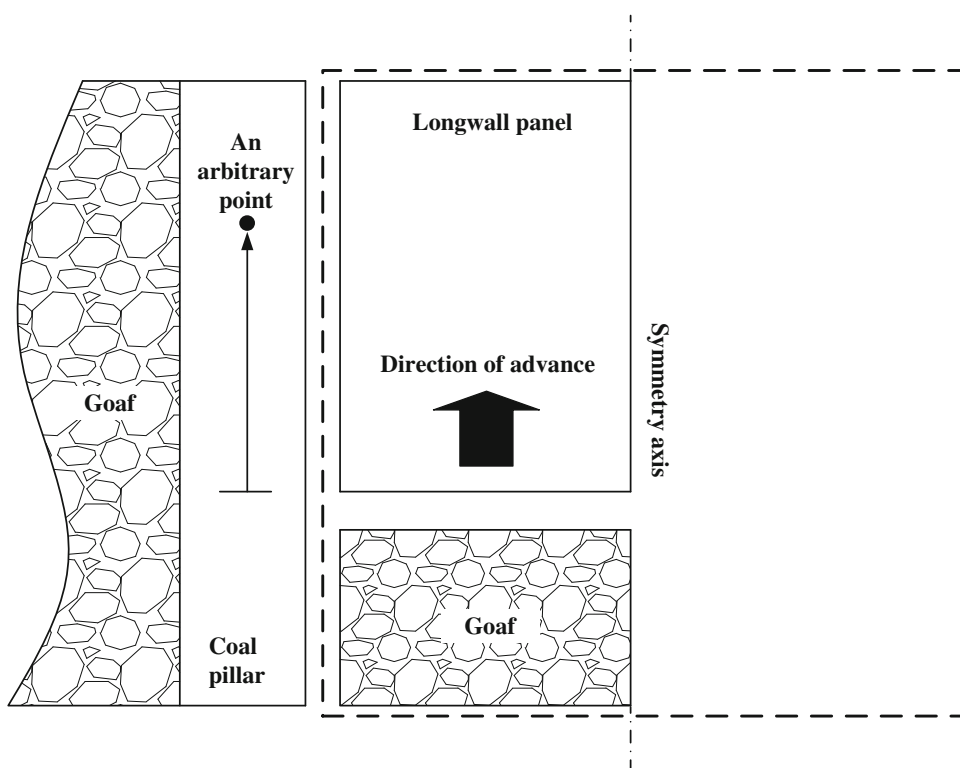


Fig. 7 Arbitrary point in the coal pillar



at 10^{-5} m/s. The elastic core is formed in the process of the compression of the model coal pillar.

The failure criterion chosen for the coal seam model is the strain-softening model based on the FLAC^{3D} Mohr–Coulomb failure model, with nonassociated shear and associated tension flow rules (Fama et al. 1995; Hoek 1990; Jiang et al. 2009; Pietruszczak and Mro 1980; Singha et al. 2002; Wang et al. 2011; Zhou et al. 2009). In this model, the cohesion and the friction angle can be adjusted to soften the material after the onset of plastic yielding by employing a user-defined piecewise linear function (Itasca Consulting Group Inc. 2006). In the standard

Mohr–Coulomb model, these properties remain constant. The mechanical parameters applied in this simulation are shown in Fig. 3, to obtain a reasonable load–deformation relationship. For the coal pillar under uniaxial compression, the boundary conditions are set around the numerical model as indicated in Fig. 4. Because the area represented is only one-quarter of the pillar through the symmetry cuts, the displacement of the four vertical symmetry planes of the model are restricted in the normal direction, and a zero vertical displacement condition is set at the base of the model.

The stress–strain curve can be drawn according to the deformation of the coal pillar. Figure 5 shows the

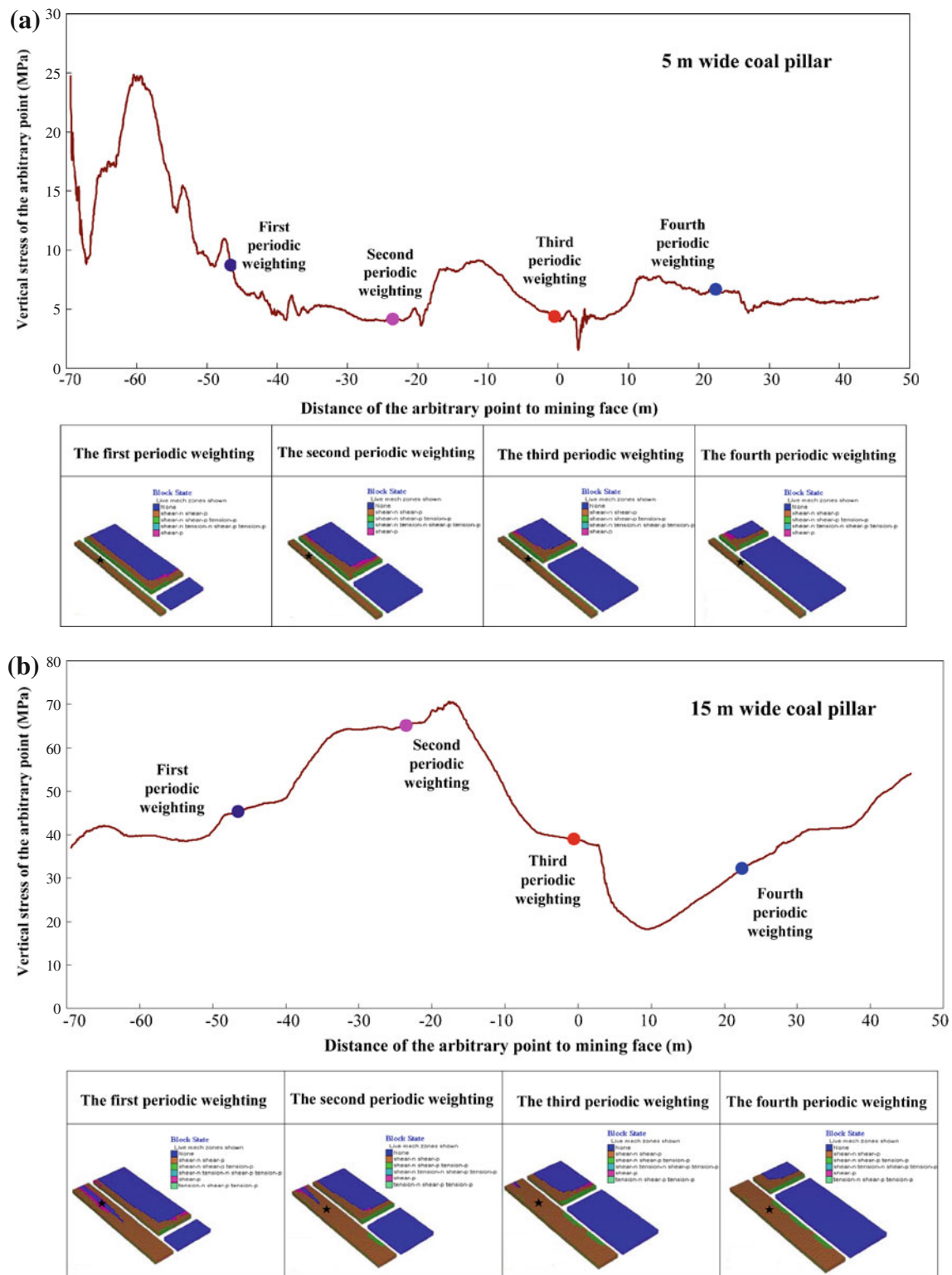


Fig. 8 Vertical stress and plastic state during the fourth periodic weighting: **a** 5-m-wide coal pillar, **b** 15-m-wide coal pillar, **c** 20-m-wide coal pillar, and **d** 30-m-wide coal pillar

stress–strain curve with the variation in the elastic core (indicated in blue in Fig. 5) of the coal pillar during the loading process. A gradual decrease in the volume of the

elastic core can be observed in the figure. The stress–strain curve can be divided into elastic and plastic parts. The volume of the elastic core of the coal pillar can be observed

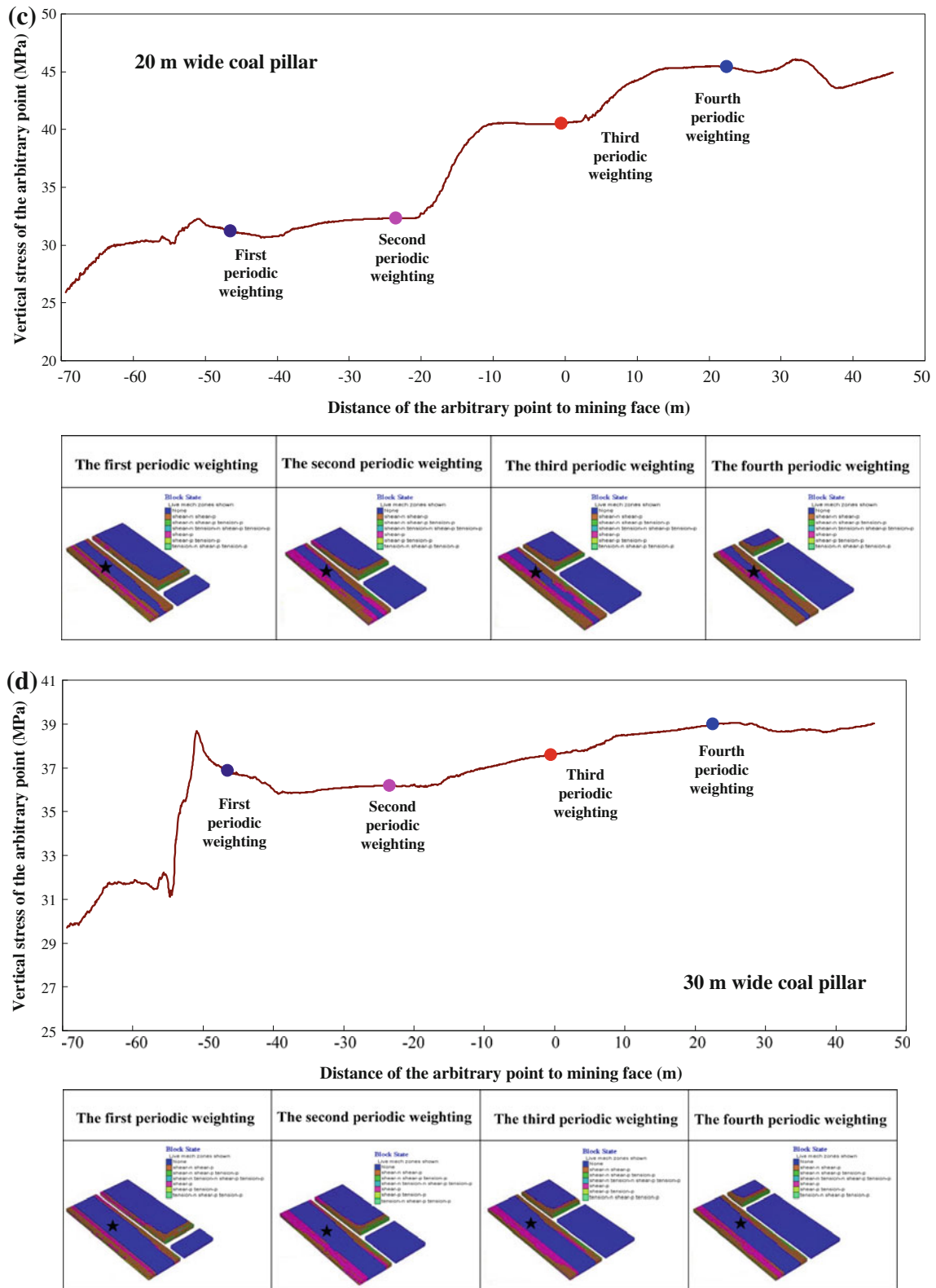


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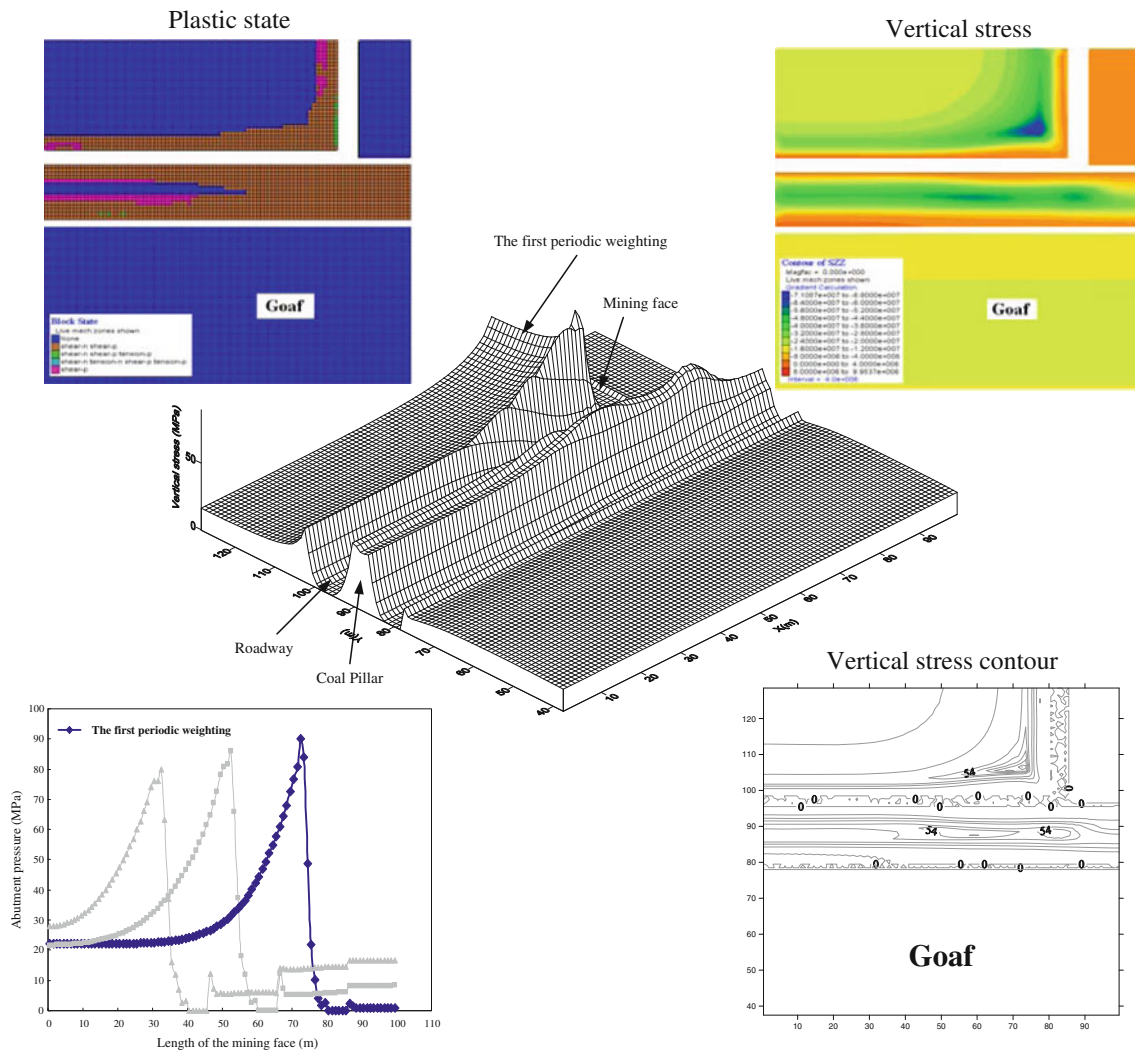


Fig. 9 Abutment stress of the island longwall mining panel during periodic weighting: **a** first periodic weighting, **b** second periodic weighting, and **c** third periodic weighting

at the peak strength in the plastic part of the curve. It is indicated that the vertical stress of a coal pillar with large elastic core is expected to be greater after the peak in the stress–strain curve has been reached.

4 Dynamic Vertical Stress of the Coal Pillar in the Longwall Panel

4.1 Numerical Modeling and Simulation Scheme

FLAC^{3D} was employed to simulate the stress distribution in the T₂193_A panel. The numerical model assumes a length of 700 m in the dip direction, a width of 500 m in the strike direction, and a height of 300 m, as shown in Fig. 6. In this model, the simulated height of the coal seam is 3 m. The element size for the coal seam is a constant $1.0 \times 1.0 \times 1.0 \text{ m}^3$, whereas the element size for the roof

and floor is $2.0 \times 2.0 \times 2.0 \text{ m}^3$. The width of the coal pillar is 15 m, and the roadways are 4 m wide and 3 m thick. To obtain the stress distribution in the panel, reasonable boundary conditions are established for the numerical model. The horizontal displacements of the four vertical planes of the model are restricted in the normal direction, and the vertical displacement at the base of the model is set to be zero. At the top of the model, a vertical load ($p = \gamma H$) is applied to simulate the overburden weight. Based on extensive data from in situ stress measurements at the Tangshan coal mine, both stress coefficients in the x - and y -directions (horizontal plane) are set to be 0.8. To simulate the falling of the roof during panel extraction, both the coal seam and the immediate roof are extracted in the process of modeling. During the extraction, the goaf area is filled by a very soft elastic material to approximately simulate the support capability of the fallen rock from the roof. The Young's modulus of this material

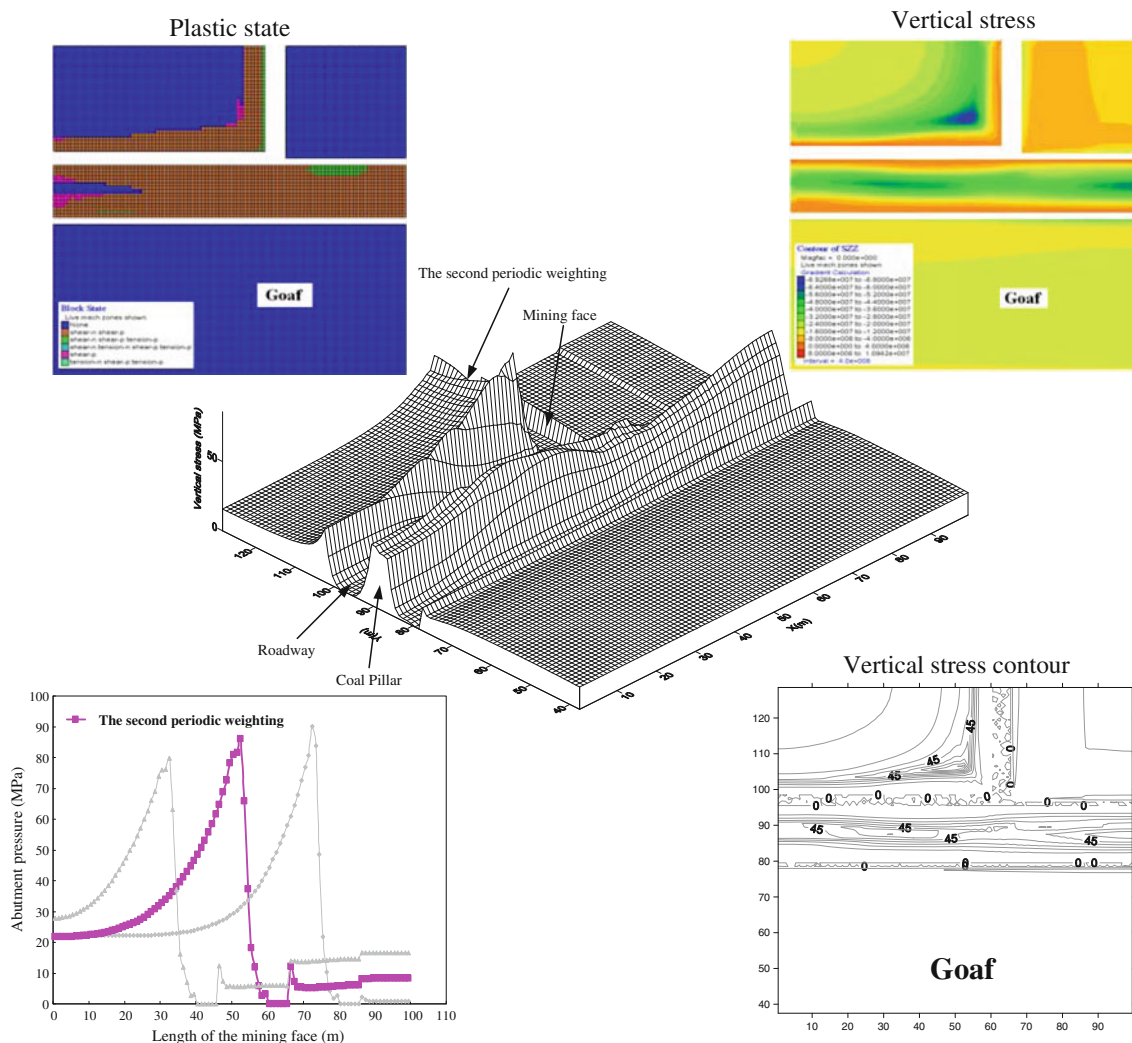


Fig. 9 continued

is set at 190 MPa, and the Poisson ratio is 0.25 (Cheng et al. 2010; Wang et al. 2011; Jiang et al. 2012).

The elastoplastic Mohr–Coulomb model with nonassociated flow rules is chosen as the failure criterion for the coal, roof, and floor strata (Fama et al. 1995; Hoek 1990; Jiang et al. 2009; Pietruszczak and Mro 1980; Singha et al. 2002; Wang et al. 2011; Zhou et al. 2009). The mechanical parameters applied in this simulation are shown in Fig. 3.

4.2 Dynamic Vertical Stress of the Coal Pillar

To investigate the dynamic mechanical state of the coal pillar during longwall mining, an arbitrary point in the coal pillar was selected for analysis of the vertical stress and plastic state, as shown in Fig. 7.

In this study, the coal pillars are 5, 15, 20, and 30 m wide and 3 m thick. The vertical stress and plastic state of the arbitrary point during the fourth periodic weighting are

presented in Fig. 8. The results in this figure show that the maximum vertical stress increases with increasing coal pillar width. The wider the coal pillar, the greater the volume of the elastic core. Based on these results, a coal pillar with large width could be made to form a larger elastic core volume. Therefore, the vertical stress is expected to be large in magnitude. Because of this high stress and the associated stored elastic energy, the risk of coal bumps in a coal pillar with large width is greater than for a coal pillar with small width.

4.3 Abutment Stress Distribution of an Island Longwall Panel

As mentioned in Sect. 3, the T₂193_A panel is a typical island longwall panel because both sides are surrounded by previously extracted panels. In underground mining engineering, an island longwall panel is a special type of coal

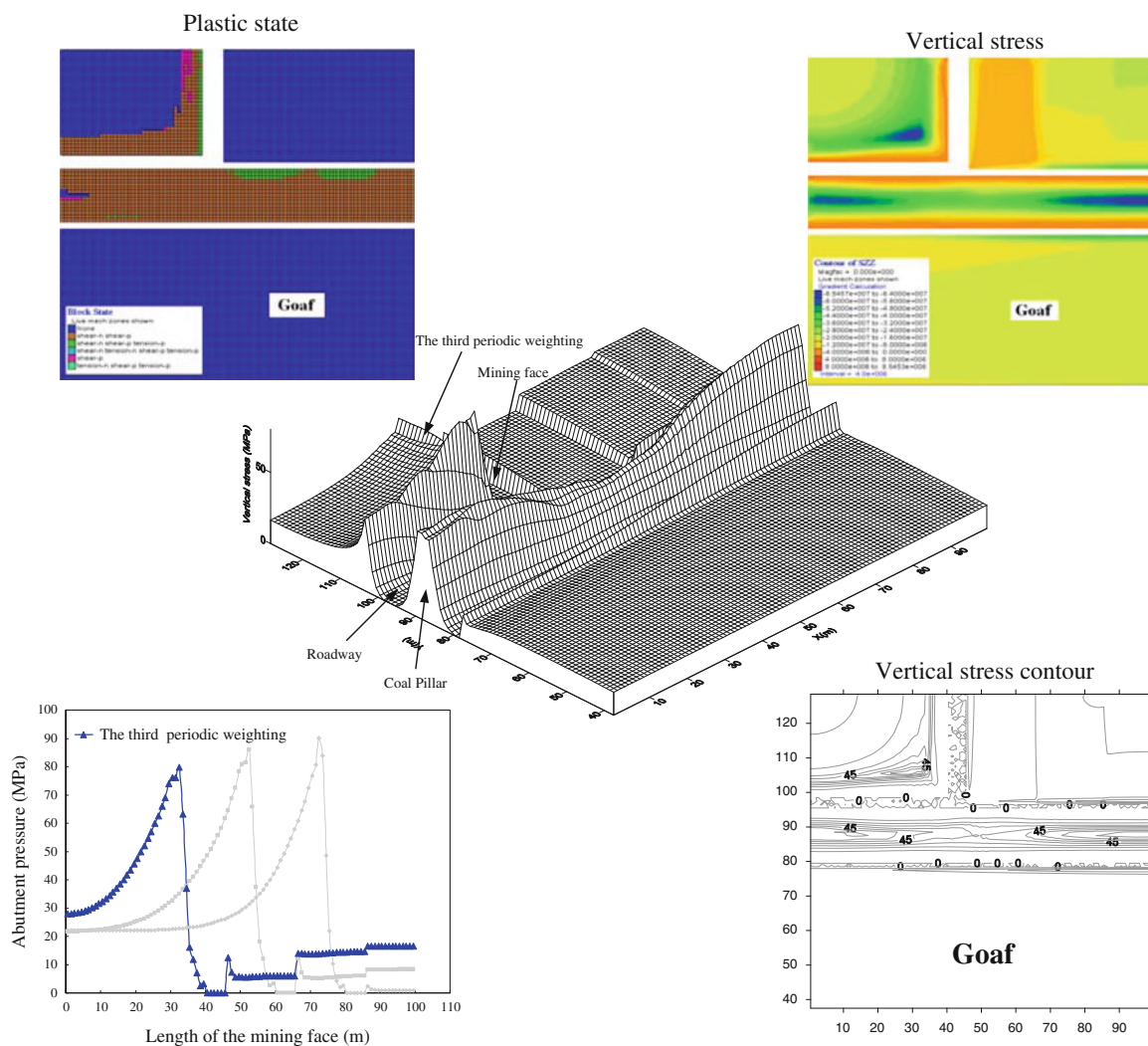


Fig. 9 continued

pillar. Due primarily to the stress concentration in the pillar or island panel, one of the most challenging engineering problems is to avoid coal bumps and catastrophic failures at the working face (Huang et al. 2007; Liu et al. 2007; Shen et al. 2008; Wang et al. 2002). Therefore, it is necessary to analyze the mechanical state of this panel. Figure 9 shows a 3D view of the abutment stress distribution in the vicinity of the panel during periodic weighting. It can be observed from the figure that the abutment stress induced by the working longwall face is relatively low near the face but increases quickly in front of the face. The peak abutment stress occurs at the intersection of the mining face and the roadway. The location of the peak stress region moves forward with every periodic weighting event of the immediate roof.

The magnitude of the mining-induced stress, which is formed when the mining face is extracted, gradually increases during the mining process. The peak mining-induced stress is reached when the periodic weighting occurs. The abutment stress distribution during periodic

weighting in the panel along the strike is shown in Fig. 9. It can be observed from Fig. 9 that the stress is relatively low near the mining face but increases sharply in front of the mining face. These results suggest that the abutment stress reaches a peak value at a distance of 7.5 m in front of the mining face. The length of the influence zone induced by mining is approximately 30 m in front of the island longwall face.

5 Conclusions

Numerical investigations were conducted for the T₂193_A longwall panel of the Tangshan coal mine to determine the dynamic mechanical state of the coal pillar. The main conclusions drawn from the investigations can be summarized as follows:

1. The progressive failure of a coal pillar under uniaxial compression occurs from the pillar boundary towards the center. There is still an intact core when the peak pillar strength has been exceeded. This central portion

of the coal pillar plays a significant role in its loading capacity. In this study, the intact core of the coal pillar is defined as an elastic core.

2. The wider the coal pillar, the greater the volume of the elastic core. Therefore, a coal pillar with large width could form a larger elastic core, and as a result, the vertical stress is expected to be greater. Because of this high stress and the associated stored elastic energy, the risk of coal bumps in a coal pillar with large width is greater than for a coal pillar with small width.
3. The model results predict that the peak abutment stress occurs near the interaction between the mining face and the roadways at a distance of 7.5 m from the mining face. The peak stress zones move forward with each periodic weighting event from the immediate roof. The region of influence induced by the panel extraction is located approximately 30 m in front of the mining face. It is revealed that the bump-prone zones around the longwall panel are within 7–10 m ahead of the mining face and near the edge of the roadway during panel extraction.

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