



Verification of 3D Numerical Modeling Approach for Longwall Mines with a Case Study Mine from the Northern Appalachian Coal Fields

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Abstract

Accurately estimating load distributions and ground responses around underground openings plays a significant role in the safety of the operations in underground mines. Adequately designing pillars and other support measures relies highly on the accurate assessment of the mining-induced loads, as well as the load-bearing capacities of the supports. There are various methods that can be used to approximate mining-induced loads in stratified rock masses, both empirical and numerical. In this study, the numerical modeling approach recently developed at West Virginia University, which is based on the modeling approach developed by the National Institute for Occupational Safety and Health (NIOSH), is investigated using the finite difference software FLAC3D. The model includes the longwall panels, the adjacent chain pillar systems, and the different stratigraphic layers of the overburden. Using the 3D model, changes in loading conditions and deformations on the areas of interest, induced by an approaching longwall face, can be examined. This paper details the 3D modeling of a longwall panel utilizing this approach, and the verification of the results against field observations. The studied panel was 360 m wide with a 3-entry chain pillar system and about a 160-m average overburden depth around the studied area. The overburden strata consist of alternating layers of shale, sandstone, and limestone. The FLAC3D results were compared against field measurements from the mine site. The stress change values measured in the chain pillars were comparable with the modeling results. The model also replicated the surface subsidence profile obtained from field measurements fairly well. Overall, the 3D modeling approach was found to be successful for the case study longwall panel.

Keywords Coal mining · Longwall mining · Finite volume model · Flac3D · Northern Appalachian

1 Introduction

Accurately estimating mining-induced load distribution and resulting ground response in underground mines plays a significant role in pillar and ground support design, hence in the safety of mining operations. There are different methods, both empirical and numerical, that can be used to assess load transfer that takes place during panel retreat. In cases where more complex stress changes are expected, calibrated numerical models can be used [1]. The numerical models are based on fundamental laws of

physics and approximate the geo-mechanical behavior of the coal and overburden. Since geologic material rarely follows theoretical behavior, models must be carefully calibrated, and model outputs are as reliable as the reliability of model input.

Numerical modeling is becoming more widespread in mine planning, design, and case analyses. The inherent improvement in numerical modeling software and computer hardware has highlighted the benefits of inclusion in the advancement of the science of rock mechanics associated with underground coal mining. Numerical models further the understanding of the response of gateroads and pillars to the extraction of adjacent longwall panels [2].

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2 Mine Layout and Geologic Setting

The case study mine is a Northern Appalachian mine located in Northern West Virginia (Fig. 1). The depth of cover throughout the mine ranges from 150 to 230 m, and the typical depth is about 160 m. The longwall panels are roughly 366 m

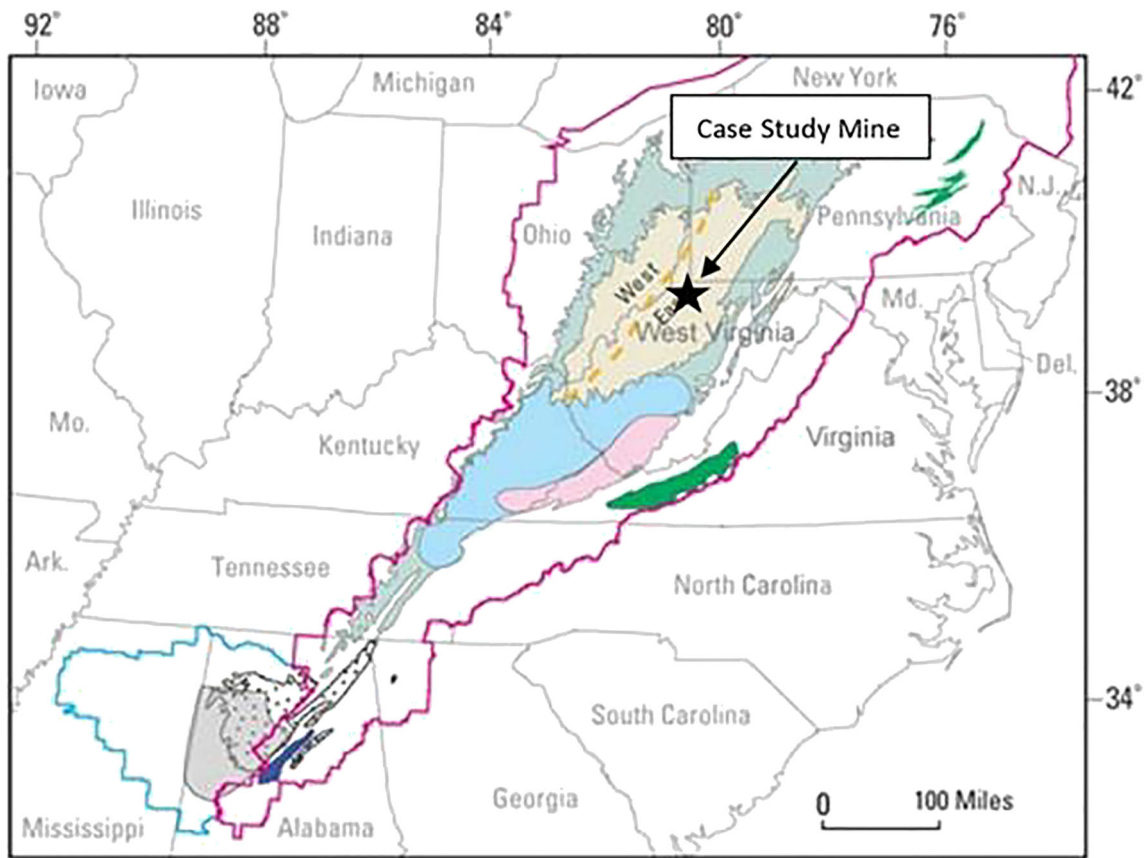


Fig. 1 Location of the case study mine [3]

wide by 2440 m long. The gateroad system is a three-entry with approximately center-to-center, 30-m-wide chain pillars with approximately 6-m-wide entries. The mining height is approximately 2.1 m [4].

The mine is operating in the Middle Kittanning coal bed and the geologic conditions are typical for the Allegheny Formation. Figure 2 shows the stratigraphy of the overburden in this area that consists of alternating layers of shale,

Fig. 2 Stratigraphic column of the case study mine

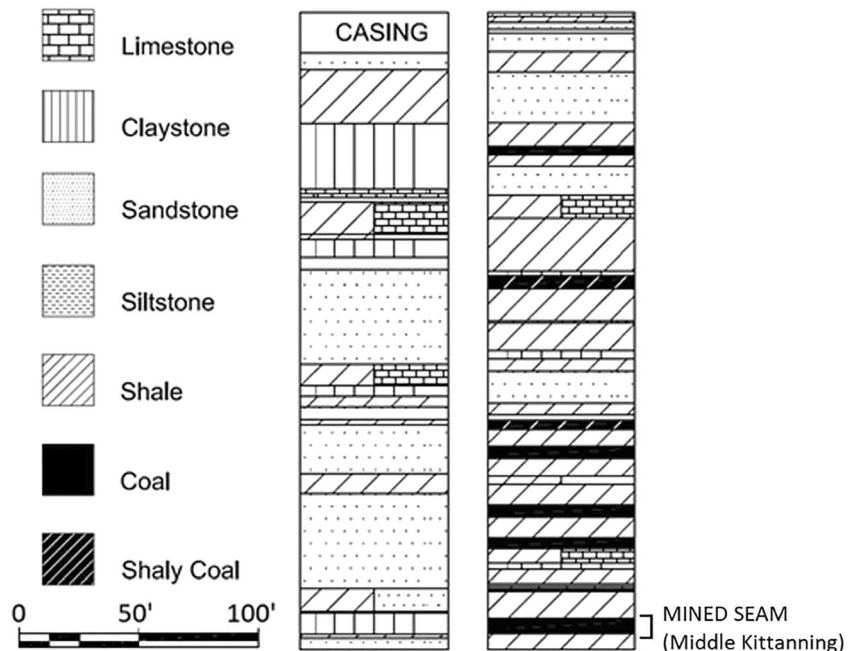
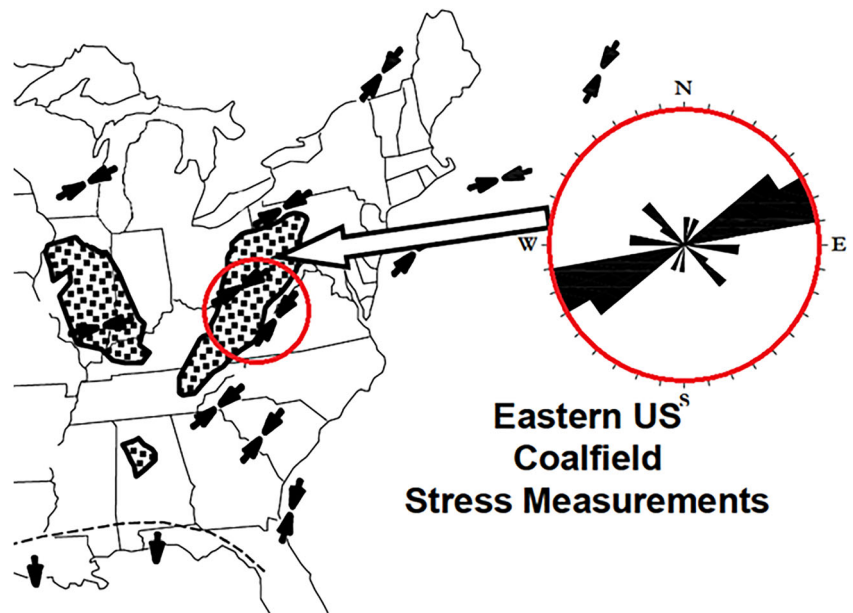


Fig. 3 Horizontal stress orientations in Eastern US coalfields [5]



sandstone, and limestone. The coal is overlain by dark gray to carbonaceous clay shale. The clay shale changes to gray sandy shale, dark gray sandy shale, or gray sandstone going upwards. The gray sandy silt shale and dark gray sandy silt shale beds vary in grain size and sand content, based on their proximity to the laterally correlative gray sandstone beds [4].

As illustrated in Fig. 3, the mine area (Eastern US coalfields) was identified by the World Stress Map (WSM) as a stable mid-plate region with a consistent NE horizontal stress orientation [5, 6].

Horizontal stress and strain values determined by Dolinar for the Northern Appalachian coalfields are presented in Table 1 [7].

2.1 Instrumentation Layout and Monitoring Results

The study mine was instrumented in the gateroad between two active panels. The instrumentation and monitoring were done by researchers from the Pittsburgh Mining Research Division (PMRD) of NIOSH and the detailed information about the instrumentation procedure and the results are presented by Gearhart et al. [8]. The instrumentation included roof extensometers, cable bolt load cells, hollow inclusion cells, borehole pressure cells, standing support load cells, convergence sensors, and a multipoint borehole extensometer. For this

study, changes in vertical stress measured by the CSIRO hollow inclusion (HI) cells are compared with the modeling results. Figure 4 shows the location of the instrumentation site in the mine.

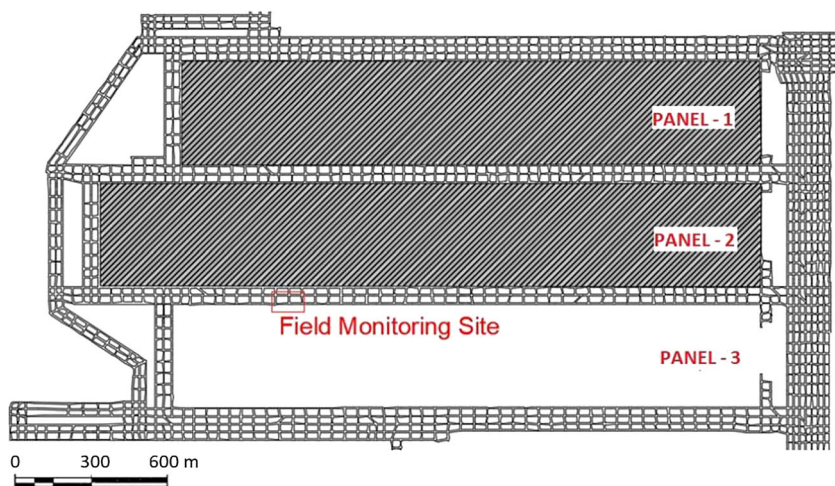
Three HI cells were installed over the solid coal of the next panel and three HI cells were installed over the pillar to measure the mining-induced stress change (Fig. 5a). The holes for the cells were drilled at angles 30, 45, and 60° from the horizontal (Fig. 5b). Two of the holes were also overcored to measure the principal stresses.

The vertical stress change was measured during both the second and third panel mining (two adjacent panels to the instrumentation site). The second panel retreat caused a 1.4-MPa stress increase over the third panel and a 1.8-MPa stress increase over the instrumented pillar. The third panel retreat caused an average increase of around 4.8 MPa over the panel and 5.8 MPa above the pillar. The response of the six HI cells can be seen in Fig. 6. The HI data shows an increase in stress after the passage of the first panel and continuing at an approximately constant rate until the approach of the second panel. During the periods when the longwall face was remote from the monitoring sites, there were not any significant roof/rib deformations detected. However, creep-like roof deformation was measured by

Table 1 Average excess applied horizontal strain for Northern Appalachian coalfields [7]

Region	Number of sites	Max. strain ($\mu\epsilon$)	Standard deviation	Range of site max. strain ($\mu\epsilon$)	Min. strain ($\mu\epsilon$)	Standard deviation	Strain ratio max/min
Northern Appalachian	7	440	90	300–540	260	70	1.69

Fig. 4 Location of the instrumentation site [4]



the roof extensometers [8] in the mine and which are concluded to be associated with the presence of clay-rich sediments such as claystone in the immediate roof and floor. These creep-like movements were the results of the constant change in the stress too.

3 Numerical Model

The finite difference software FLAC3D can model the mining-induced stresses and the related overburden behavior in terms of deformations and displacements [9]. The software can model the strength anisotropy of the bedded coal measure rocks and the weakening of the failed rocks. In addition, the built-in FISH coding language allows the user to control the loads and the displacements in the model [10]. A FLAC3D model was developed to replicate the geometric and geologic setting of the study site with a focus on the instrumentation locations at the actual study site.

3.1 Numerical Modeling Method

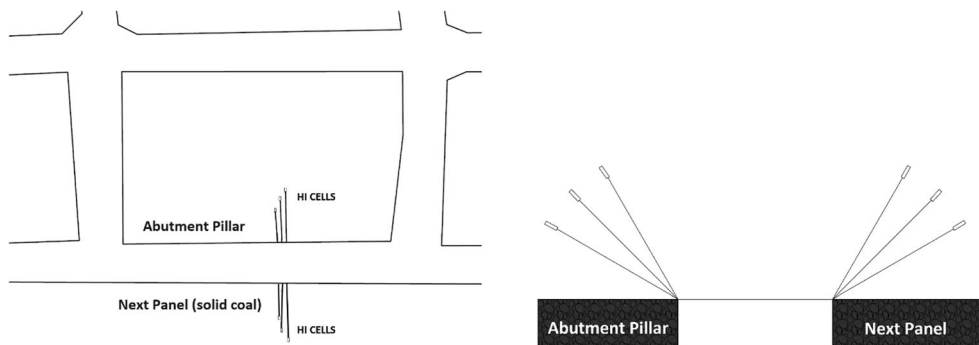
First, the 2D model is created for initial verification. The basis of the modeling methodology used in this study was

developed by Esterhuizen et al. [10]. The model includes the 2D slice of a cross-section along the width of the panel(s) with the chain pillar system. The 2D model employs actual stratigraphy, using all the geological layers as thin as 0.25 m. The overburden layers are modeled as a strain-softening ubiquitous joint material, which simulates the bedding weaknesses in strongly bedded strata and also the vertical joints in massive rock types. In 2010, Esterhuizen et al. published suggested overburden rock parameters to be used in large-scale models and were later modified by Tulu et al. [1]. The updated parameters are used for this study, and they are explained in detail by Tulu et al. [1].

In addition to the model developed by Esterhuizen et al., interface elements are used to model the interfaces between the geological layers in the overburden. As described by Su, the coefficient of friction of interfaces was set to 0.25 [11]. Joint shear stiffness was set to 50 GPa/m, and normal stiffness was set to 100 GPa/m. The friction angle of the interfaces was selected as 15° between the overburden layers and 20° on the coal-rock interfaces to be able to simulate the appropriate stress gradient at the edge of the pillar [10].

The coal is modeled with a Hoek-Brown coal model based on the model developed in 2010 at NIOSH with the following updated input parameters [10]:

Fig. 5 Location of the installed HI cells. (a) Plan view. (b) Side view (modified from [8])



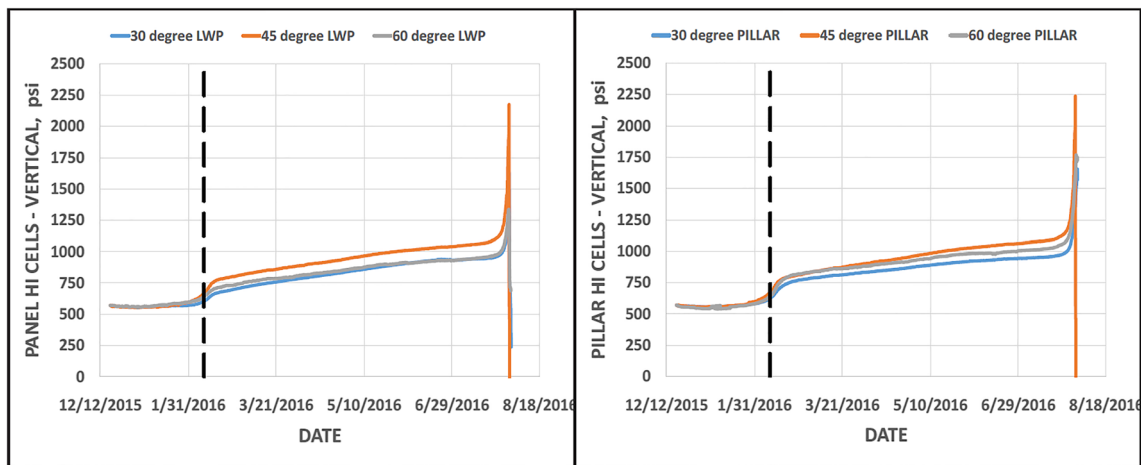


Fig. 6 Response of the installed HI cells with the dashed line showing the date the first panel passed [8]

Bulk modulus:2 GPa
 Shear Modulus:1.2 GPa
m-value:1.47 (residual: 1.17)
s-value:0.07 (residual: 0.03)
a-value:0.67
 Interface friction angle:20°
 Interface cohesion:0.375 MPa
 Interface tensile strength:0.0
 Interface normal stiffness:100 GPa/m
 Interface shear stiffness:50 GPa/m

Accurately simulating the gob response is critical to approximating the mining-induced load distribution along the chain pillars, gob, and gateroad entries. According to the study conducted by Pappas and Mark, the stress-strain response of the caved material they tested followed a strain-hardening curve [12]. The strain-hardening gob response was found to fit the hyperbolic function derived by Salamon [13]:

$$\sigma = \frac{a \times \varepsilon}{b - \varepsilon} \tag{1}$$

where:

σ vertical gob stress (MPa)
 ε vertical gob strain

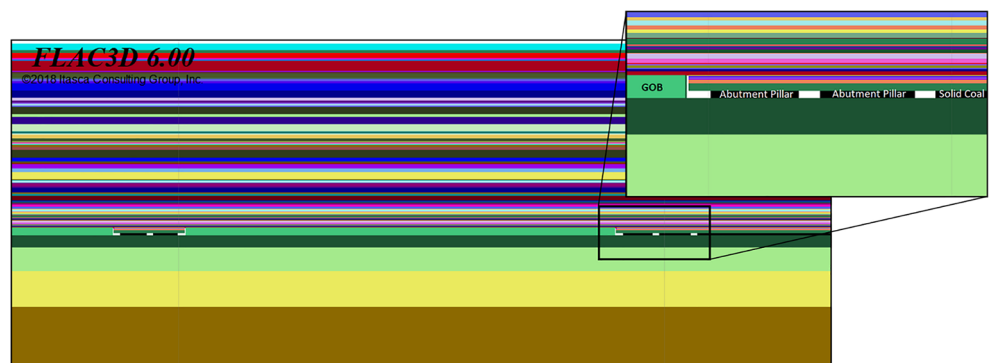
b maximum strain parameter (related to void ratio)
a gob stress (MPa) when $\varepsilon = b/2$

The FISH option of the FLAC3D software is used to simulate the strain-hardening gob behavior. It is achieved by updating the elastic modulus of each zone inside the gob with the expected tangent modulus, which can be calculated by taking the derivative of the hyperbolic function with respect to vertical strain [4].

Esterhuizen et al. examined the gob parameters, *a* and *b*, by matching the model results with subsidence profiles obtained from the Surface Deformation Prediction Software (SDPS) [14]. The maximum strain parameter *b* was determined as 0.44 and parameter *a* was found to be dependent on the type of rock material in the gob ranging from 5.9 MPa for weak gob up to 25.2 MPa for very strong gob [10].

Su assumed an initial bulking factor of 1.5 for the formation of the gob [11]. This suggests a maximum strain of 0.33 and a caving height of three times the mining height. Su has applied this approach successfully to various longwall mine cases for estimating subsidence and pillar stresses. Compared with the results obtained by Esterhuizen et al., the stress-strain values obtained from the parameters that Su used give similar results to weak/moderate gob [1]. In this study, these values are calibrated with respect to subsidence measurements from

Fig. 7 2D model geometry showing different stratigraphic layers



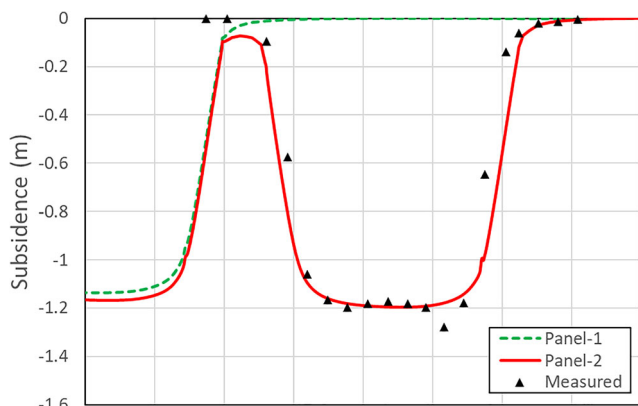


Fig. 8 Subsidence profile obtained from the 2D model

different longwall mines and the gob parameters “*a*” and “*b*” were selected as 3 MPa and 0.33, respectively.

Following the 2D model, a 3D model using the mine map is generated. In order to generate a 3D model that can run in a reasonable time frame, the minimum thickness of elements on the overburden is increased, and the lithological layers with the similar rock type are combined and represented with a transversely isotropic material model. The coal model and material properties are the same as the 2D model to produce correct dilation, peak strength, and residual strength responses while still conforming to the Bieniawski pillar strength formula [1]. The stability mapping grid generator developed for the LaModel stress analysis software is used to generate the mine layout at the seam level [15]. The instrumented pillars, roof, and floor were simulated with smaller zone sizes for more detailed analysis.

3.2 Numerical Modeling Results

Initially, a 2D model is generated with the methodology discussed in the previous section. The modeled section of the mine had 158.5-m depth of cover and a 360-m panel width. The overburden stratification obtained from a core log is modeled with layers as thin as 25 cm. There were 95 overburden layers above the coal seam, with ranging thicknesses between 25 cm and 8.2 m. The overburden layers include shale, coal, fireclay, and sandstone. The shale layers are mostly dark gray and sandy, and the sandstone layers are generally gray. Laboratory-scale uniaxial compressive strength (UCS) values for the sandstone are selected between 50 and 100 MPa, softer ones being closer to the seam level. Between 40 and 60 MPa, laboratory-scale UCS values are assigned for shales, and the fireclays were assigned 20 MPa. A total of 100 layers are modeled including the seam level and the bottom filler layers, resulting in 860,000 total number of elements. The model was 3072 elements wide and each element was 1 m wide in the *x*- and *y*-direction. Figure 7 shows the model of mine B with the bordered area showing the area of interest.

The 2D model was run in three steps to simulate development loads and two consecutive panel extractions. Figure 8 shows the surface subsidence approximated by the model and measured in the field for the mine. The maximum subsidence observed in the model was after the second panel retreat with 1.20 m, and it was 1.28 m from the field measurements. The subsidence profile obtained from the model was consistent with the monitoring results.

Figure 9 shows the total vertical stress distribution at the measurement site, after panel-2 (Fig. 4) is completely mined, approximated by the 2D model together with the stresses measured by the CSIRO hollow inclusion cells (HI cells) for the case study mine. The model approximated the abutment stresses within 10% of the field values, where installation of the instrumentation, local coal composition/strength, and calibration errors can be accounted for some of the variation.

In order to generate a 3D model that can approximate stresses accurately with larger elements, overburden lithological layers with the same rock type with thickness less than 5.0 m were combined and represented with the transversely isotropic material model. Also, the elements get larger as they get closer to the surface to keep the number of elements at a reasonable level [2, 15, 16]. The 3D model of the mine had 29 different layers and approximately 1.3 million elements. In order to generate the mine layout at the seam level, a grid generator embedded in the stability mapping application is used [17]. The instrumented pillars, roof, and floor were simulated with 1.0-m elements in the detailed area as shown in Fig. 10. Figure 10 shows two stages of increasing zone density inside the red dashed borders, encapsulating the entire study area. The geometry of the model with the representative geological sequence that was modeled is shown in Fig. 11.

Due to elements being larger near the surface, accurate subsidence profiles cannot be obtained in this 3D model. Less subsidence is observed compared with field measurements and that causes less load to fall on to the gob. In order to get reasonable loading results, the gob parameter “*a*” is calibrated to match the

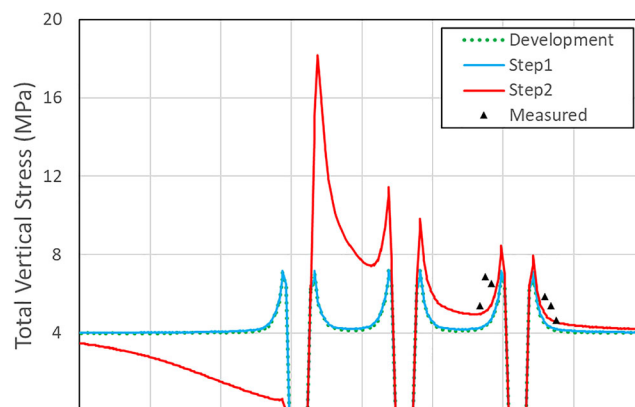


Fig. 9 Comparison of the modeled and measured stresses

Fig. 10 Modeled mine geometry showing increased zone density around the instrumentation site

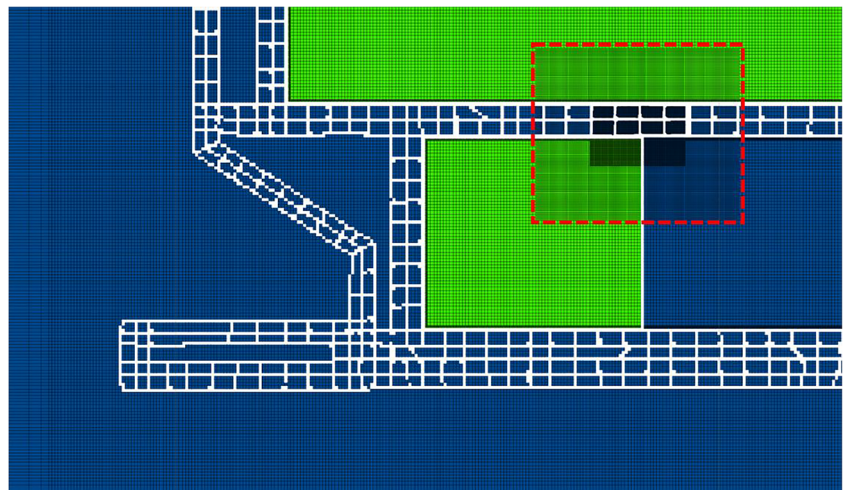
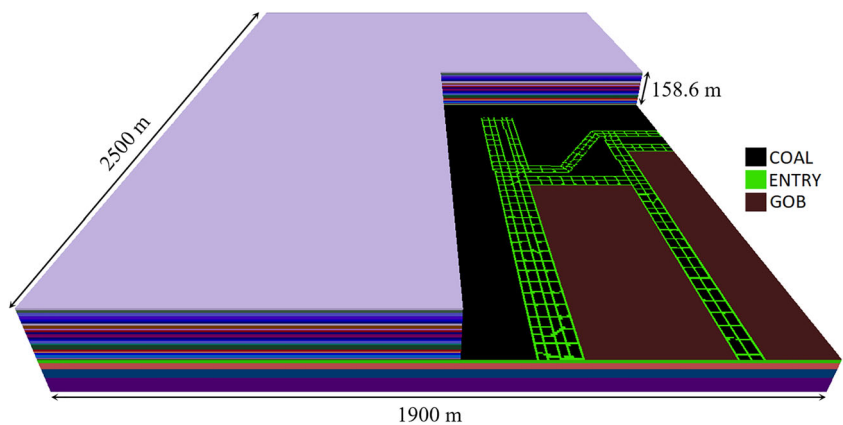


Fig. 11 The modeled geological sequence and the mining geometry



average gob stress to the 2D model. A stiffer gob is required to simulate similar gob stress considering less displacement is observed on the gob for the 3D model.

A thin slice of the 3D model that includes the larger surface elements is created to calibrate the “*a*” parameter. The average gob stress in the 2D model is calculated as 3.36 MPa. Using the original gob parameters for the 3D model ($a = 3$ MPa and $b = 0.33$), the average stress observed on the gob is calculated as 2.26 MPa. After iterating with different “*a*” values, it was found that $a = 50$ MPa gives the same average gob stress as the 2D model for the 3D model. Although the same average gob stress is achieved as the 2D model, the stress distribution shows some differences due to different convergence on the gob (Fig. 12). The main difference is observed for the pillar closer to the gob. The average pillar load is found to be 15% less than that of the 2D model for that pillar. The difference for the next pillar was less than 5%. This difference is mainly due to the difference in load extent. The 2D model simulates more abutment extent and that is the reason the 2D model shows a higher load on the first pillar and less load on the second pillar, compared with the 3D model. Overall, the difference in

average stress calculated on the pillar system is less than 8%. Further investigation of calibration methods for the 3D models will provide more accurate results. The calibration for this study only aims to match the average gob stress with the 2D model. Stress distribution and displacements can benefit from more fine tuning of different parameters of the model.

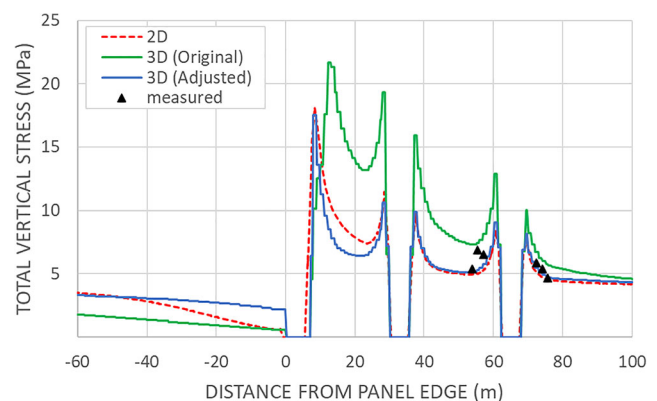


Fig. 12 Comparison of 2D and 3D model stress profiles

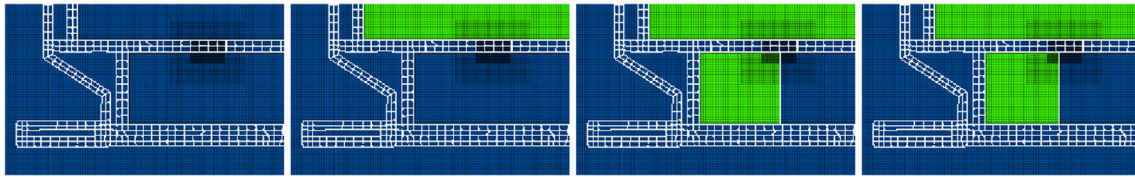


Fig. 13 (a) Development. (b) Step 1. (c) Step 2. (d) Step 3

The model was solved in four stages to simulate different face positions relative to the study site to compare with field measurements. The first stage (development) was simply the development mining scenario when all the entries in the model were mined. The second stage (step 1) was the complete retreat of the first panel, and the third and fourth stages (steps 2–3) were the longwall face of the second panel being mined about 20 m outby and 26 m inby (last available cell readings) the instrumentation site, respectively (Fig. 13).

The results of the 3D numerical model of the study area and the mining around it generally follow the anticipated trend based on the mining-induced stresses. A global view together with the close-up views of the modeled stresses for each of the four steps can be seen in Fig. 14.

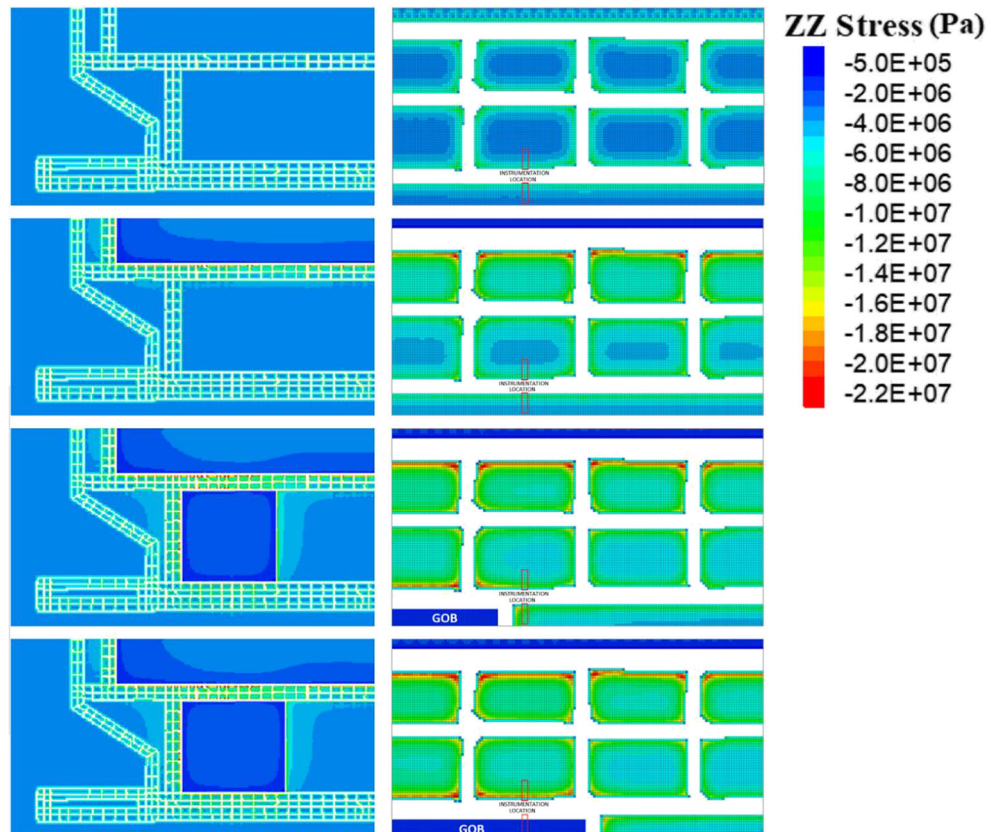
In Fig. 15, the stress profiles obtained from the 3D numerical model along the instrumentation site are presented. Profiles obtained from different steps are compared against the field measurements. This study shows that reasonable

results are obtained by the 3D numerical modeling stress results within expected accuracies. The cause of some of the variation can be due to the instrumentation installation, local composition, and strength of the material surrounding the cells, as well as the accuracy of the face position.

4 Conclusions

Accurate assessment of mining-induced loads is essential for adequately designing pillars and other support measures which play a significant role in the safety of the operations in longwall mines. There are different methods that can be used to assess load transfer that takes place during a panel retreat. In this study, a 3D numerical modeling approach is utilized for a case study mine and the results are compared and verified against collected field measurements. Initially, a 2D numerical model is generated using the method developed by Tulu et al. [1], which is

Fig. 14 Modeling steps and the resulting vertical stress



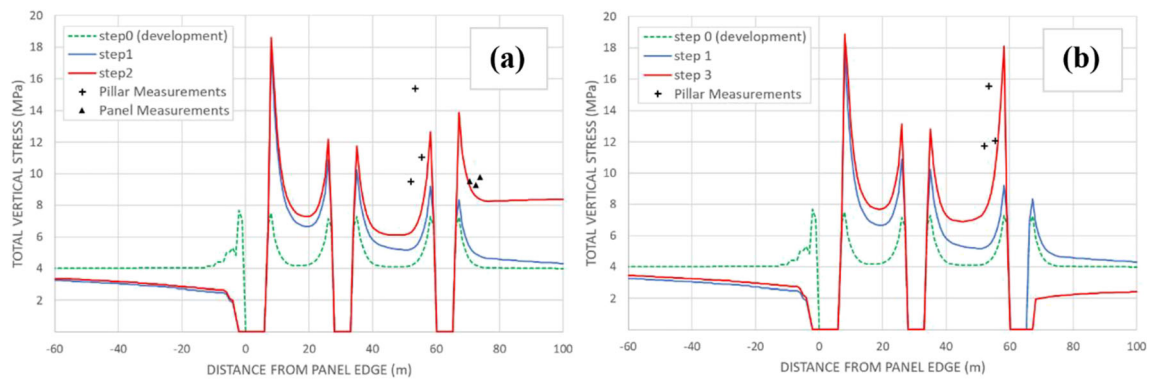


Fig. 15 Stress profile from the 3D model when the panel is (a) around 20 m in by the instrumentation site and (b) 20 m out by the instrumentation site

based on a modeling approach developed by NIOSH. After getting satisfactory results compared with the available field measurements, the 3D numerical model is generated. Required calibrations are made for the gob parameters in order to match the results obtained from the 2D model. This need for calibration arises due to larger element sizes generated for the 3D model. A stiffer gob is required to simulate similar gob stress for the 3D model, considering original parameters result in less displacement observed on the gob. The calibrated 3D model gave comparable results to the field measurements within expected accuracy; however, there is still progress to be made in calibrating the 3D model to obtain as detailed results as the 2D models. Although 2D models can simulate stresses in more detail due to more detailed element sizing, its disadvantage comes when induced stresses around tailgate junctions need to be investigated. It can be concluded that a calibrated 3D numerical method can be useful to simulate mining-induced loads with respect to different locations of the panel face where more complex stress changes can occur.

Authors' Contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Deniz Tuncay, Ihsan Berk Tulu, and Ted Klemetti. The first draft of the manuscript was written collaboratively by all authors. All authors read and approved the final manuscript.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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