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NUMERICAL SIMULATION OF STRESS CONCENTRATIONS ON PILLARS IN A TYPICAL LONGWALL MINE

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Keywords

Underground Coal Mining, Longwall Mining, Distinct Element Method, Stress Analysis.

Abstract

Coal is still the major resource to meet the expanding energy demand and widely used in coal-fired thermal power plants taking the advantage of rich reserves and cost-effective production. Longwall mining is a method that is widely used in Türkiye, in line with the trend in the world, that enables the economical and sustainable production of underground coal resources with mechanized equipment. Estimation of stress distribution and concentration zones in the excavation face and roof is critically important in terms of determining the appropriate hydraulic support properties in production by longwall mining. Advancing the wide excavation face along the mining direction causes in-situ stress distribution in the rock mass to change and the stresses associated with the excavation to intensify. This may trigger potential instability events. This study investigates the relationship of stresses developed on pillars due to longwall production with pillar dimensions and field loadings in a typical underground coal mine using numerical simulations. Parametric analysis was performed on three-dimensional models using Distinct Element Method. The simulation outputs characterize the performance of alternative pillar designs under different field loading conditions, in terms of stress distribution and concentration zones that will develop due to production.

TİPİK BİR UZUNAYAK MADENİNDE TOPUK GERİLMELERİNİN SAYISAL SİMÜLASYONU

Anahtar Kelimeler

Yeraltı Kömür Madenciliği, Uzunayak Madenciliği, Ayrık Eleman Yöntemi, Gerilim Çözümlemesi.

Öz

Kömür, zengin kaynaklar ve maliyet etkin üretim avantajları sunması nedeniyle günümüzde halen en sık kullanılan ve genişleyen enerji talebini karşılamak üzere termik santrallerde değerlendirilen bir yakıttır. Uzunayak madenciliği, yeraltı kömür kaynaklarının mekanize ekipmanla ekonomik ve sürdürülebilir üretimini mümkün kılan, dünyadaki eğilim ile örtüşür şekilde ülkemizde de yaygın olarak kullanılan bir yöntemdir. Uzunayak üretiminde kazı arını ve tavanda gelişen gerilim dağılımı ve yoğunlaşma bölgelerinin kestirimi uygun hidrolik tahkimat özelliklerinin belirlenmesi açısından kritik seviyede önemlidir. Geniş kazı aynasının ayak boyunca ilerletilmesi, kaya kütlesinde doğal gerilim akışının değişmesine ve kazıya bağlı gerilimlerin yoğunlaşmasına neden olmaktadır. Bu durum potansiyel duraysızlık olaylarını tetikleyebilecek niteliktedir. Bu çalışma, tipik bir yeraltı kömür işletmesinde uzunayak üretimine bağlı olarak topuklar üzerinde gelişen gerilimlerin topuk boyutları ve arazi yüklemeleri ile ilişkisini sayısal simülasyonlar ile incelemektedir. Üç boyutlu modeller üzerinde ayrık eleman yöntemi ile parametrik analiz yapılmıştır. Simülasyon çıktıları, alternatif topuk tasarımlarının farklı saha yükleme koşulları altında performansını üretime bağlı gelişecek gerilim dağılımı ve yoğunlaşma bölgeleri türünden karakterize etmektedir.

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NUMERICAL SIMULATION OF STRESS CONCENTRATIONS ON PILLARS IN A TYPICAL LONGWALL MINE

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Highlights

- Geomechanical simulations are useful for parametric study of various operational practices
- The Distinct Element Method (DEM) conforms the discontinuous nature of coal beds
- The field stress ratio controls the stress concentration on pillars and abutment pressures
- The pillar instability and violent failure potentials were investigated by stress analyses

Purpose and Scope
The paper aims to investigate the stresses concentration within the coal pillars regarding various production sequences in a typical longwall operation.

Design/methodology/approach
The stress and deformation analyses on coal pillars were carried out by three-dimensional numerical modeling when multiple panels are produced in a typical longwall mine. The effects of the pillar shape and field stress ratio were investigated by parametric studies. Due to the bedded stratification of the coal basin, a discontinuous modeling approach was embraced.

Findings
Production of multiple longwall panels in a large coal seam can result in stress concentration on the pillars nearly four times the before production state. The most critical pillars are the ones where the longwall retreat begins. Excessive loads have potential to cause dynamic failure in pillars. The rectangular pillars are more effective in reducing the stress despite the loss of coal. The stress distribution on the pillar cross-section increases outward from the center and may cause pillar bursts in brittle rocks such as hard coal. The material model is critical to effectively simulate the abutment pressures.

Research limitations/implications
Despite the discontinuous nature of the distinct element method provides better mechanical simulations for longwall mining, the complex structural network dramatically increases the computational costs. GPU accelerated numerical codes may provide computational advantages.

Practical implications
The practical implication of this study is its potential to grow a concern about the field stress ratio and its mechanical effects on longwall mining.

Originality
The paper is significant in terms of investigating various geomechanical properties (like field loading conditions), mine design parameters (like pillar geometries) and numerical variables (like the material model) in an iterative manner. The stress concentrations were examined during the different production stages. In this aspect, the study may provide a basis to establish the operational safety while the production still goes on.

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1. Introduction

Global trend towards alternative sources to sustain gradual shift to zero emission industry until 2030 and 2050 have not yet replaced the fossil fuels as today still 35% of energy production is based on coal (IEA, 2022). Although coal use was decreasing until 2020 with the determined actions and policies of governments to gradually close inefficient power plants and support companies to invest in alternative sources, a strong return trend has been experienced as of 2021 due to the increase in natural gas prices triggered by global political instabilities. It can be predicted that coal resources are indispensable or irreplaceable in the near term, especially when considering the energy need due to industrialization and population growth in developing countries.

Recovery and efficiency are the key parameters for sustainable management of coal resources in Türkiye as the exploitable reserves and calorific value are very limited and shares only 1.1% of the total reserves in the world (BP, 2022). The longwall method, which was developed in England at the beginning of the 17th century, is widely used in underground coal mining with the integration of advanced production technologies, as well as in Türkiye, as it is all over the world, with its high efficiency, fast production and cost advantages compared to alternatives. The method poses a mine layout with rectangular production panels by dividing the horizontal or shallowly dipping coal seam with two parallel excavations, called the ‘headgate’ and the ‘tailgate’. Exploitation goes on from the coal face perpendicular to the roads and executed by means of mechanical extraction. A typical longwall panel as presented in Figure 1 from the cross-section view involves a set of ‘self-advancing hydraulic supports’ that resist the roof pressure, a ‘shearer’ for production, and an ‘armored face conveyor’ for transporting the coal parallel to the excavation face. In practice the height of the hydraulic support can reach up to 6 m, which allows to excavate the entire span from thin seams. However, thick seam excavation is a geomechanical challenge as it leaves a large space that is prone to instability. Top coal caving method provides a safe and cheap alternative for production from thick coal seams. In this case, the coal recovered from roof caving is transported by the rear conveyor system installed behind the hydraulic support.

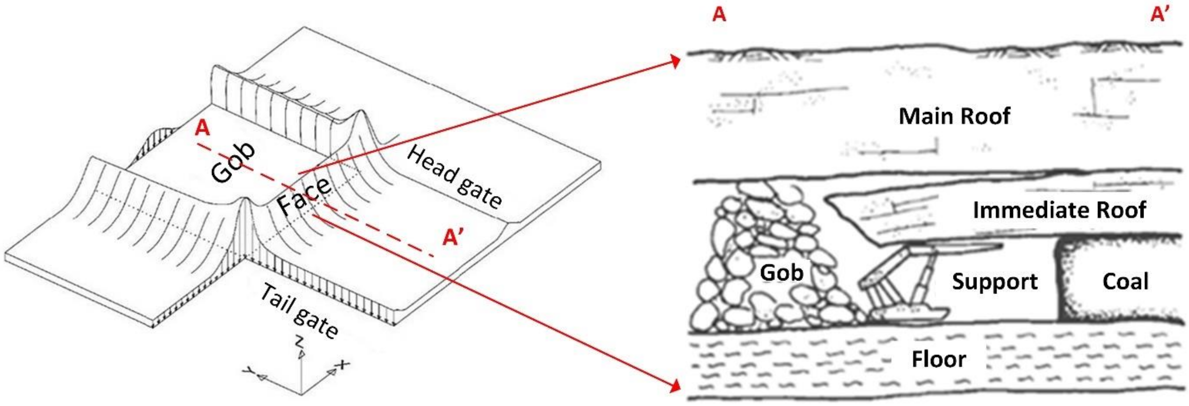

Figure 1. Stress distribution and cross-section view of a typical longwall panel (Sasaoka, et al., 2020; Barczak, 1992)

Along with the advantages that longwall mining provides in terms of production speed and amount, there is a potential for problems such as overpressure on hydraulic supports, uncaved roof strata behind the shields and subsidence on the topographical surface. A common practice to operate safely from panels is leaving a body of in-situ coal strata called ‘pillar’ to resist the roof pressure. Although the seam recovery reduces, coal pillars are inevitable to maintain panel stability during production.

Prior to production the coal seam is under the influence of vertical loadings originating from the overburden and horizontal field loads. According to the numerical simulation studies of various researchers, the stresses were observed to concentrate around the roadways and behind the excavation face, as seen in Figure 1.

Roadway and coal face instabilities are frequent events that result in fatalities and loss of production. Studies have shown that the geological structure, production plan and excavation can manipulate the virgin field stress distribution around these regions (Gao et al. 2017). There are several empirical (Yavuz, 2002) and analytical (Wagner,1980) methods for pillar design. All of them rely on some assumptions that are valid under specific conditions and may need to be revised due to changing operating conditions, geological structure and geomechanical characteristics. In geomechanics, numerical modeling provides flexibility and reliability by easily adapting to different conditions to explore the complete mechanism. Specifically in longwall mining, it allows to carry out parametric studies of pillar stability for different dimensions, production patterns and field conditions.

This study investigates the stresses concentrating within coal pillars due to production in a typical longwall operation. Parametric analyses were performed on numerical simulations to reveal the effect of pillar dimensions, shape and field stress with the stress concentration on pillar. Distinct element method was used in three-dimensional numerical models to implement the strata as it is capable of considering the structural discontinuities and bedding planes. Certain production stages were simulated and maximum principal stresses on pillars were followed to observe the performance of different pillar designs operating under various field stress conditions. Development of induced stresses on pillars related with the advance of coal face was examined.

2. Instability Problems in Longwall Mining

Related to the excavation geometry, instability problems may occur due to stress concentration along the coal pillars, at the back of the coal face and along the roadways. Stress concentrations controlled by seam depth, field stresses, rock mass elastic properties and stress-strain characteristics may cause plastic deformations (crack formation and propagation) followed by failure, as well as a more destructive and dynamic type of failure called rock burst under extreme magnitudes (Crouch, 1973). Rock burst, which is a common problem of deep underground metallic mines, has recently been a challenge of hard coal enterprises following the commissioning of deep seams due to depleting majority of shallow coal resources. In coal strata, this violent instability problem is specifically called 'coal burst'. Although it can be seen on the headgate and tailgate, pillars and immediate roof, the most common type develops at the coal face. In order to predict coal burst events, micro-gravity method, micro-seismic method and support monitoring technique are used. Destressing can be considered as a measure to control this violent instability event. It is most widely implemented in terms of destress blasting. It works on the basis of creating crack networks by blasting in the region where stress concentrates. Another method is to induce crack formation by drilling empty holes in stress concentration zones. It has been observed that this method is time consuming and unreliable. Finally, dynamic failure potential can be mitigated by increasing the saturation.

Sudden collapse of the immediate roof where caving is expected but could not be achieved due to stiff strata is another emerging instability problem. In this case, the roof strata will behave as a beam and exert excessive load on hydraulic support.

The large volume of excavation in a coal seam leads to deformations in the roof stratum. Advancing the excavation face, significant deformations, called as subsidence, can be observed on the ground surface. Subsidence is an inevitable event, which may cause critical damage on constructions. Intensity of the subsidence depends on the time, the depth of the production opening, the seam thickness and the strength of the overburden. Another risk posed by surface subsidence is its capability to control the groundwater flow. The cross-section view in Figure 2 illustrates a typical subsidence event due to excavation of a horizontal seam.

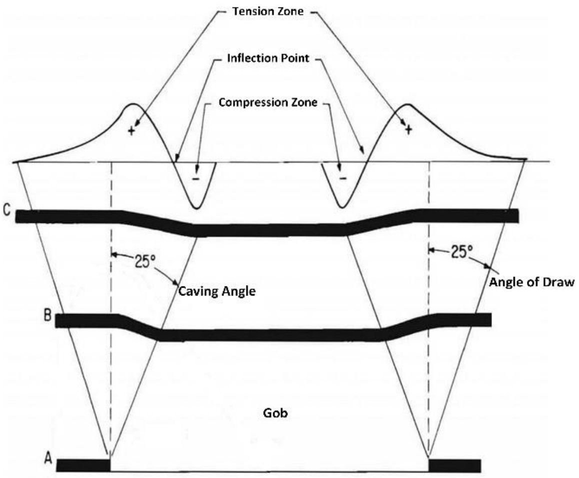

Figure 2. Illustration of a surface subsidence event from the cross-section view (Haycocks et al., 1982)

Rib pillars can provide a better safety along the roadways during exploitation. Since the coal left in the pillar body causes loss of production, chain pillars composed of multiple square or rectangular bodies are considered to be more advantageous in terms of the recovery. Barrier pillar is another support element between panels and it has a wider span.

Panel and pillar dimensions can be determined based on empirical approaches (Mark and Gauna 2021), while numerical models propose improved reliability by stress and strain analyzes. Mechanical simulations based on continuous and discontinuous techniques are widely used in strata control, pillar design, roadway stability and support design. There are many studies investigating roadway stability (Sasaoka et al. 2020), pillar stability (Singh et al. nd) and caveability (Singh and Singh 2020) with two or three-dimensional numerical models.

3. Pillar Design

A pillar is an unmined portion of the orebody and most frequently used to support not only the overlying strata but also a portion of the neighboring areas on the roof. The span of this tributary area is considered to be half of the opening width. For square and rectangular pillars, the concept is illustrated in Figure 3.

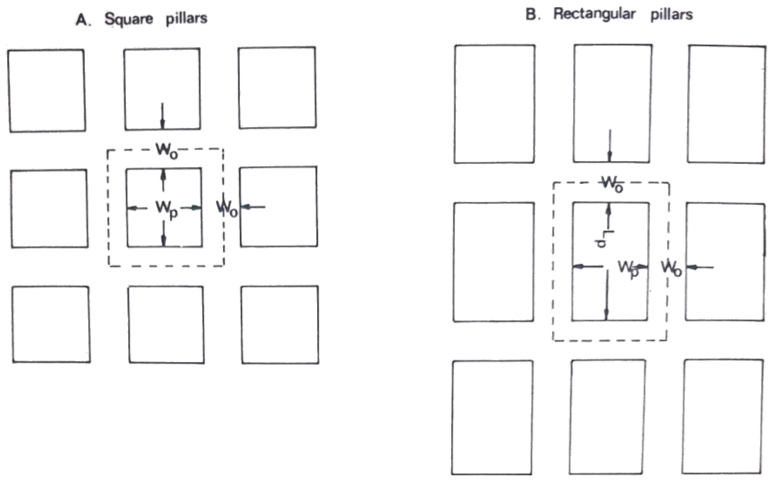

Figure 3. Tributary area loading concept for square and rectangular pillars (Peng, 1978)

Under these circumstances, the average stress on square (1 and 2) and rectangular (3 and 4) pillars are calculated from:

$$\frac{P}{W^2} = \frac{\left(W_o + W_p\right)^2 \rho g h}{W_p^2} \quad (1)$$

$$\sigma_a = \left(1 + W_o/W_p\right)^2 \sigma_v \quad (2)$$

$$\frac{P}{L_p W_p} = \frac{\left(L_p + W_o\right)\left(W_o + W_p\right)\rho g h}{L_p W_p} \quad (3)$$

$$\sigma_a = \left(1 + W_o/L_p\right)\left(1 + W_o/W_p\right)\sigma_v \quad (4)$$

Where σ_a is the average pillar stress; P is the total load on the pillar; L_p,, W_p and W_o are the widths of pillars and rooms or entries and σ_v is the vertical stress.

Although the first scientific approach to pillar design was based on experiments carried out by Bunting on cube samples of different sizes in the early 20th century, many researchers subsequently proposed equations to predict pillar loading based on laboratory experiments and field-scale studies (Jawed et al., 2013). The tributary area theory, which is commonly used to estimate the loads for square or rectangular pillars, lacks a realistic understanding of stress distribution as it assumes a uniform configuration.

Right after the excavation, a destressed zone above the opening causes the vertical loads to shift outwards to both sides of the panel. Because of its shape, this destress zone is called as 'pressure arch'. Field studies in the European coal fields point out that the span of the pressure arch is correlated with the depth, which may be expressed as in (5):

$$W_{pa} = 0.15h + 60 \quad (5)$$

Where W_{pa} is the minimum width in feet of the maximum pressure arch and h is depth in feet. Depending on the pressure arch concept, a rough estimation can be made about the abutment pressures as seen in Figure 4.

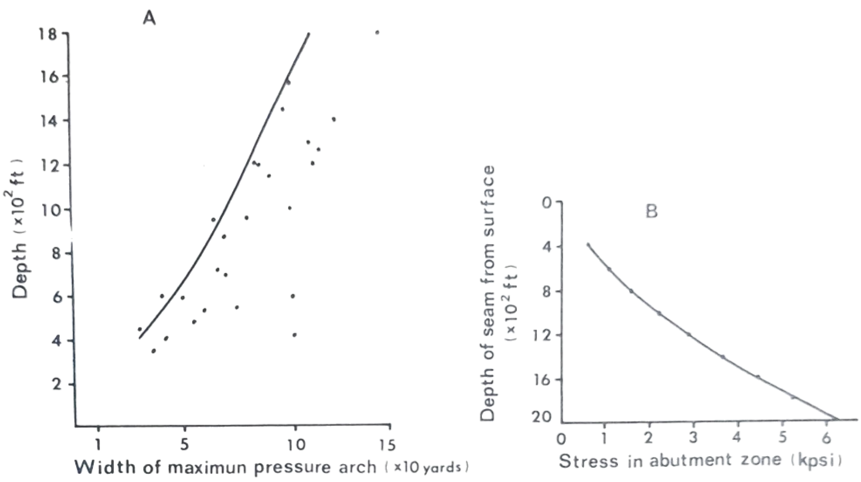

Figure 4. (A) width of maximum pressure arch, (B) estimated maximum stress in the abutment zone (Peng, 1978)

Chain pillar and rib pillar are used in longwall mining to support the roadways along the panels. While rib pillar extends along the roadway with no break, chain pillars are a system of square or rectangular individual pillars that have an offset distance between each other. The distance contributes to the coal recovery; however, the reliability of the pillar is affected.

The coal strength, which is the main parameter to determine pillar strength, can be found by laboratory tests on cubical or cylindrical samples of 2 to 6 in or alternatively, in-situ tests provide a better understanding of pillar strength but they are costly and not practical. Due to the size effect, it is well-known that smaller samples have higher strength. Therefore, coal samples of up to 60 in. were found to be better for determination of the pillar strength (Peng, 1978). As a result of lab tests, the relationship between the size and the strength of the specimen was formulated as in (6)

$$S_1 = K_1 + d^{-a} \quad (6)$$

Here, S_1 is the uniaxial compressive strength of the cubical specimen, d is the side length of the specimen and K_1 and a are constants that depend on the seam. The range of possible value for K_1 and a were determined by numerous lab-tests (Peng, 1978)

Shape is even a more critical parameter affecting the strength of coal pillar and the general expression given in (7) defines the strength based on shape effect.

$$S_2 = K_2 + (W^b/H^c) \quad (7)$$

Where S_2 is the uniaxial compressive strength of the coal pillar, which is W in width and H in height, K_2 is the strength of the cubical pillar, and b and c are constants.

Another pillar type is the 'barrier pillar', which is left to support main entries or mined out panels. Despite there are several empirical expressions, the most frequently used one is given in (8)

$$W_p = \frac{h}{10} + 45 \quad (8)$$

Here, W_p is the barrier pillar width in feet and h is the depth in feet.

4. Numerical Simulation of Production in a Typical Longwall Mine

This study examines the stress concentrations that develop in pillars when multiple panels are produced in a typical longwall mine using three-dimensional numerical modeling. The effects of different shape and field stress conditions on pillar performance were studied. Considering the stratification of various geological layers involving the coal seam, a discontinuous modeling approach was embraced using Itasca 3DEC, which is a 'distinct element method' code. Figure 5 shows the model geometry, strata, production stages and pillars. Model dimensions are 320 x 320 x 450 m. Five horizontal layers were created to simulate the coal seam at a depth of 400 m, which are a floor stratum at the bottom, 4 m thick coal seam, 10 m thick 'immediate roof (I.R.)', 20 m thick 'main roof (M.R.)' and 370 m thick 'overburden (OB.)'. Mine layout dimensions were set to 110 m for the panel width, 25 m for the length and 5 m for the roadway width. Chain pillars were studied in three different dimensions, which are 20x20 m, 20x30 m and 20x40 m. Longwall retreat method was simulated for a large coal seam that needs to be extracted via multiple panels.

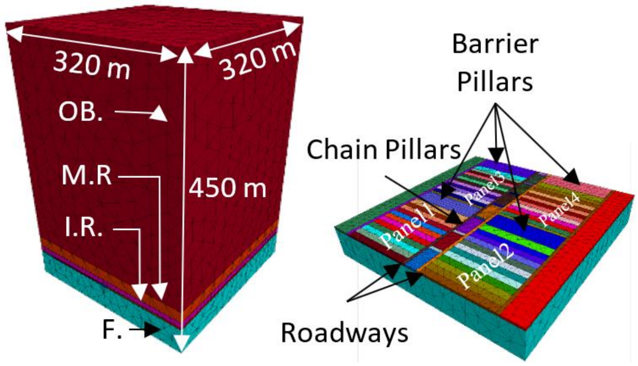

Figure 5. The numerical model geometry

The rock mass properties of the strata were obtained from a previous study in the literature (Singh & Singh 2010) in which the longwall method was examined within the scope of field and laboratory studies. Representative values are assigned for the interlayer contact properties. The material properties used in the numerical models are presented in Table 1. Each distinct stratum was considered as continuous media and the Mohr-Coulomb elastic-perfectly plastic material model was defined. Mohr-Coulomb slide model was used for the contact surfaces. The layers were formed as deformable blocks and tetrahedral volumetric elements were used to fill the volume for numerical calculations. Mesh element dimensions are densified around the pillars and immediate roof. Field stresses were studied for three different cases, which are k=0.5, k=1 and k=1.5.

Table 1. Numerical model input parameters (Singh and Singh 2010)

Continuous Media					
Mechanical Properties	OB.	M.R.	I.R.	Coal	F.
Density (kg/m^3)	2200	2000	2100	1400	2300
Modulus of Elasticity (GPa)	6,5	5,7	6,7	2,0	5,7
Poisson Ratio	0,25	0,25	0,25	0,25	0,25
Cohesion (MPa)	2,5	2,1	2,4	1,2	2,1
Internal Friction Angle (°)	40	40	40	25	40
Tensile Strength (MPa)	1,0	0,8	1,0	0,5	0,8

Discontinuities				
	k_n (GPa/m)	**k_s (GPa/m)**	**c (MPa)**	**φ (°)**
Interlayer contacts	100	10	1	30

*
OB. = Overburden, M.R. = Main roof, I.R. = Immediate roof, F. = Floor
k_n = Normal stiffness, k_s = Shear stiffness, c = Cohesion, φ = Internal friction angle

Production steps have been set to 10 meters in each advance for two neighboring panels. The model was first run with elastic material properties with no excavation. After defining the plastic material properties roads were excavated. The next stages involve the step-by-step simulation of production. First, production was started on the left panel by excavating 10 m slices in each stage. After completing this panel, a similar advance was followed in the adjacent panel on the right. 30 m thick barrier pillars were left between the main road and panels. In order to follow the effect of each excavation stage in terms of the maximum principal stress on the pillars, a history point was defined at the midpoints of each pillar. Since 3DEC carries out iterative analysis based on calculation time, the development of stress concentrations in the pillars could be observed. Stress contours were obtained along the pillars and other critical regions using the simulation outputs.

5. Numerical Analysis of Stress Concentration on Pillars

Stresses developed in the coal pillars due to the advance in production panels were investigated in each calculation step. Within the model geometry, a total of 13 pillars were formed in a 20 x 20 m square arrangement. The maximum principal stresses at the midpoints of four representative pillars were plotted versus the calculation step and presented in Figure 6. Total number of calculation steps considering the force balance in each model stage was reported to be 105500. It should be noted that the Itasca 3DEC uses classical mechanical notation and therefore compression is shown with a minus sign in the graphs.

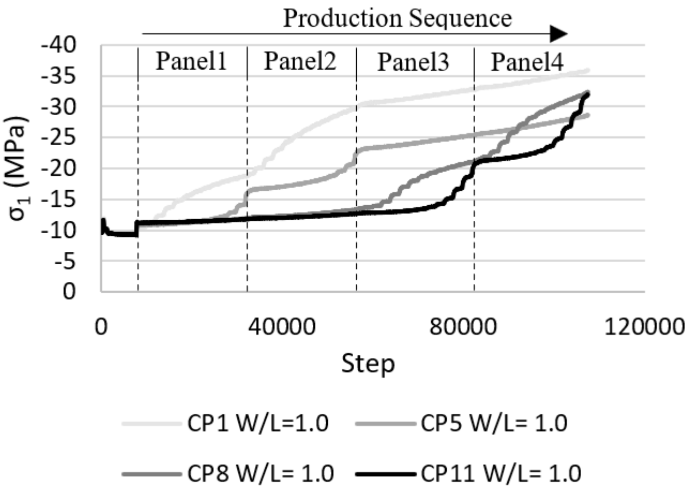

Figure 6. The maximum principal stresses when k=1,0 and square pillar dimensions are 20x20 m

The pillars were assigned with a unique code regarding the production sequence in a retreat operation with an increasing number through the main road. The maximum principal stress history of the pillars numbered one, five, eight and eleven were plotted to observe production related stress accumulations. The simulations for k=1.0 implying the lateral and vertical field stresses are equal in a 400 m-depth operation and for the end of production only in the front-left panel have shown that the maximum principal stresses in the first pillar have increased approximately 2 times while for the fifth pillar the increase is approximately by 1.5 times. The following production milestone, which is the end of exploitation in the adjacent panel on the front-right, points out an increase in the maximum principal stress at the first pillar by approximately 3 times; however, this increase was observed to be approximately 2.4 times in the fifth pillar. No significant effect of production on the front panels was observed on the rear panels. When the production is completed in all of the panels, 3.7 times stress concentration was observed on the first pillar compared to the pre-production stage. This value was observed as 3 times in the fifth pillar, 3.4 times in the eighth pillar, and approximately 3.3 times in the eleventh pillar. At this point, it should be reminded that the first and fifth pillars are located between the front panels, and the nineth and thirteenth pillars are between the rear panels. The simulation outputs turn out that the concentration in the sixth pillar remained at the level of 2.4 times. In the thirteenth pillar, this ratio is around 1.7 times. This is because sixth pillar is close to the barrier pillar that separates the front and rear panels, and similarly the thirteenth pillar is close to the barrier pillar of the rear panels. Thus, it can be concluded that the barrier pillars are useful to reduce the stress accumulation on the square pillars.

In the next step, a total of seven pillars were fitted in the layout with a rectangular arrangement and dimensions of 20 x 40 m. Four representative pillars were determined to plot the maximum principal stress at the midpoints of pillars versus the calculation steps and presented in Figure 7.

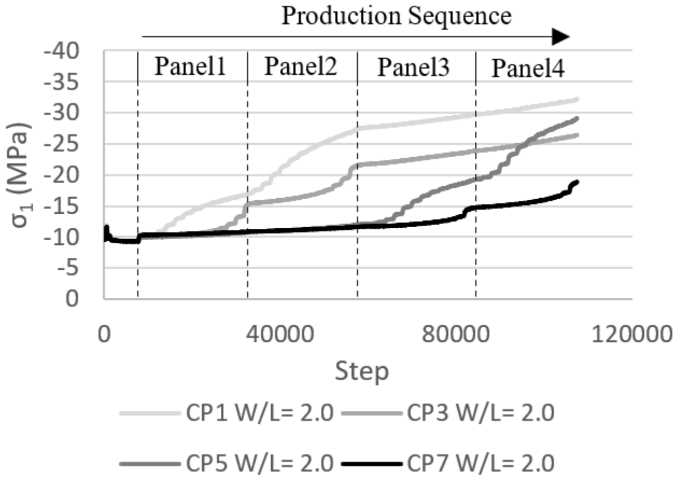

Figure 7. The maximum principal stresses when k=1.0 and rectangular pillar dimensions are 20x40 m

In this case, when production was completed on the front-left panel only, the maximum principal stress in the first pillar increased by approximately 1.6 times and in the third pillar this increment is approximately by 1.5 times.

When the production goes on from the front left panel, at the end of excavation the stresses concentrate by 2.7 times on the first pillar compared to the pre-mining stage. The third pillar, which is within the front panels and close to the main road has a stress accumulation of approximately by 2.2 times. Similar to the previous model, no significant effect of the front panels was observed on the rear panels. When production was completed from all of the panels, the maximum principal stress increased by 3.4 times in the first pillar, 2.8 times in the third pillar, three times in the fifth pillar, and doubles in the seventh pillar, compared to pre-mining stage. Compared to square cross-section, the rectangular pillars take advantage of a larger area to distribute the vertical loads, and therefore stress concentrations decrease. However, the coal recovery is affected negatively.

The effects of different field stress conditions and pillar geometries on pillar stress concentration were investigated in parametric analysis, Figure 8 shows the distribution of the maximum principal stresses on a section line along the pillars in the first phase of production and the stress history on the first pillar for different pillar dimensions. The simulation points out that the stress concentration on pillars reach the highest value when the 20 x 20 m square pillar arrangement (the ratio of dimensions is 1) is used. In rectangular pillars, as the length of the long axis increases, stress accumulates less and the risk of pillar failure decreases.

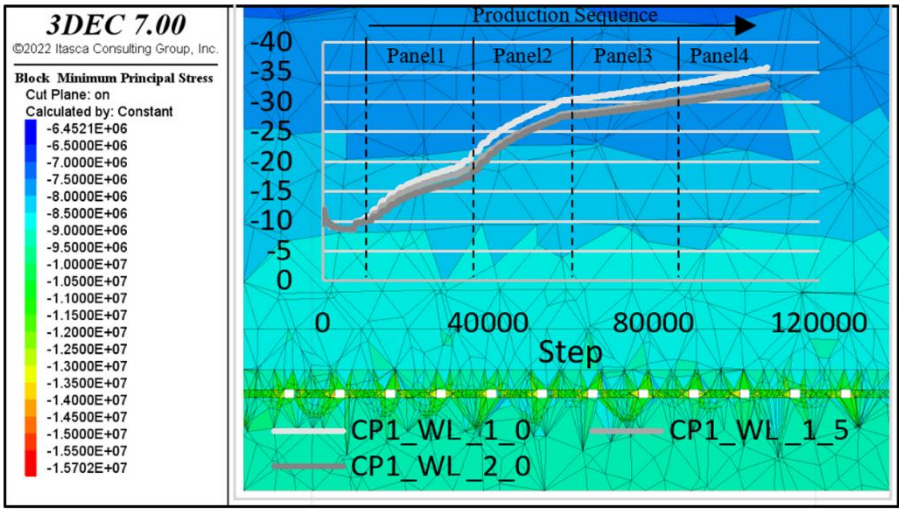

Figure 8. The maximum principal stress for different pillar geometries when k=1.0

In Figure 9, the maximum principal stresses contours on the same section line passing along the pillars were presented for the end of production in all panels. The stress history was also plotted for the first pillar under different field stress conditions. It was determined that when the horizontal field stresses are higher, more stress accumulation occurs within the first pillar during the production of the first panel. However, the difference due to the horizontal field stresses diminish to a large extent as the excavation continues in the other panels.

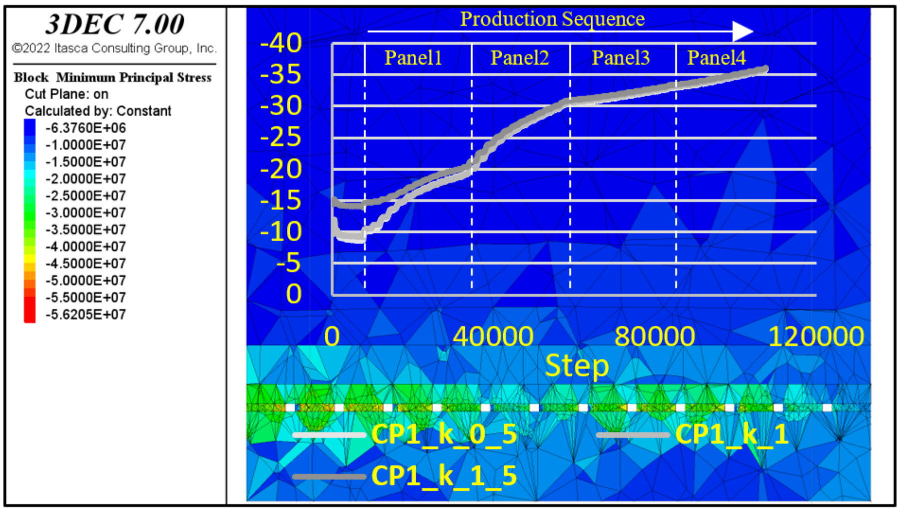

Figure 9. The maximum principal stresses for square pillar arrangement and different field stresses

Figure 10 shows the stress distributions in a cross-section perpendicular to the excavation direction on the fourth square pillar, when k=1. Accordingly, it can be predicted that the stresses increase relatively around the excavation boundaries compared to the center of the pillar. This is due to the abutment pressures applied to the outer extents of pillars by the yielding immediate roof stratum. The stresses can increase up to 3 times in these regions close to the free surfaces compared to the center and may cause pillar burst in hard coal pillars.

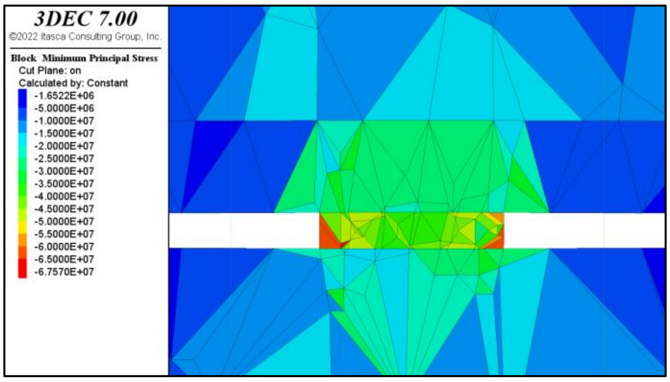

Figure 10. The maximum principal stress contours on the fourth pillar when k=1.0 and all panels are produced

Figure 11 presents the stress concentrations in the rock mass surrounding the pillars when the production is completed in all panels. The top view of a horizontal cross-section was taken from the middle of the coal seam and the gob material was filtered in order to clearly observe the stress concentrations. It was noted that the stresses increased significantly in the immediate vicinity of the free surfaces around the roadways and behind the coal face, and the concentration was observed at a level of up to 3.5 times, in line with the visual presented in Figure 2, which theoretically represents the stress concentrations expected to develop at the end of a single panel production. Considering the fact that square pillars operate under uniaxial loading and the level of stress concentration is taken into account, it can be predicted that the pillar recovery potential is reduced.

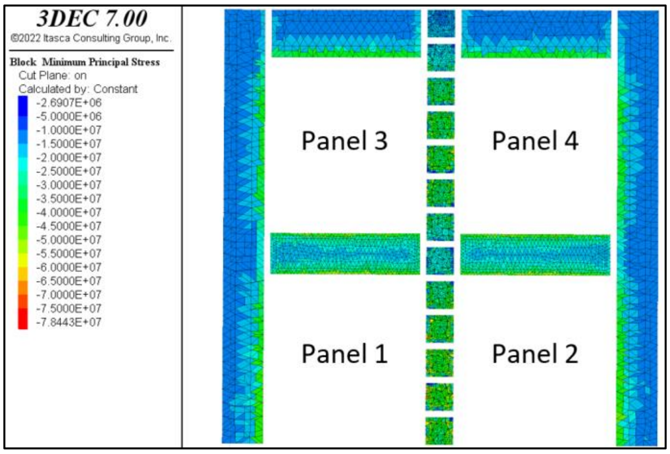

Figure 11. The maximum principal stress distribution around the longwall panels after production is completed (k=1.0 and square pillars)

As the stress concentration increases around the produced panels, the material behavior shifts from elastic to plastic, which implies the generation of fractures and cracks in the rock mass. Further loading of a plastic material concludes up with the failure. As shown previously in Figure 10, the stress on a pillar tends to show a higher concentration close to the free faces compared to the center in the early stages of loading. In other words, pillar deformation is likely to start from the outer boundaries as plasticity initiates on those regions earlier compared to the center. The common practice for numerical investigation of stress concentration is to carry out elastic analyses. However, this study takes advantage of plastic models to observe the propagation of stress concentrations through the center of the pillar as the outer extents yield due to the excessive loadings. Figure 12 shows the yielded elements around produced panels for two significant production sequences. The models denote three different field stress conditions, which are k=0.5, k=1.0 and k=1.5. The light-colored regions depict elastic materials while the dark colors imply the yielded regions. According to the simulations, the yielded regions within the pillars cover more than 50% of the whole cross-section for k=0.5. In other words, pillars completely fail when the vertical stresses are greater compared to the horizontal stresses. However, k=1.0 and k=1.5 models show that the yielded elements do not expand more than 20% of the pillar cross-section. Under these circumstances, deformations may be expected around the free-faces and stress concentrates through the center. A similar trend also shows up for the barrier pillar and roadway sides.

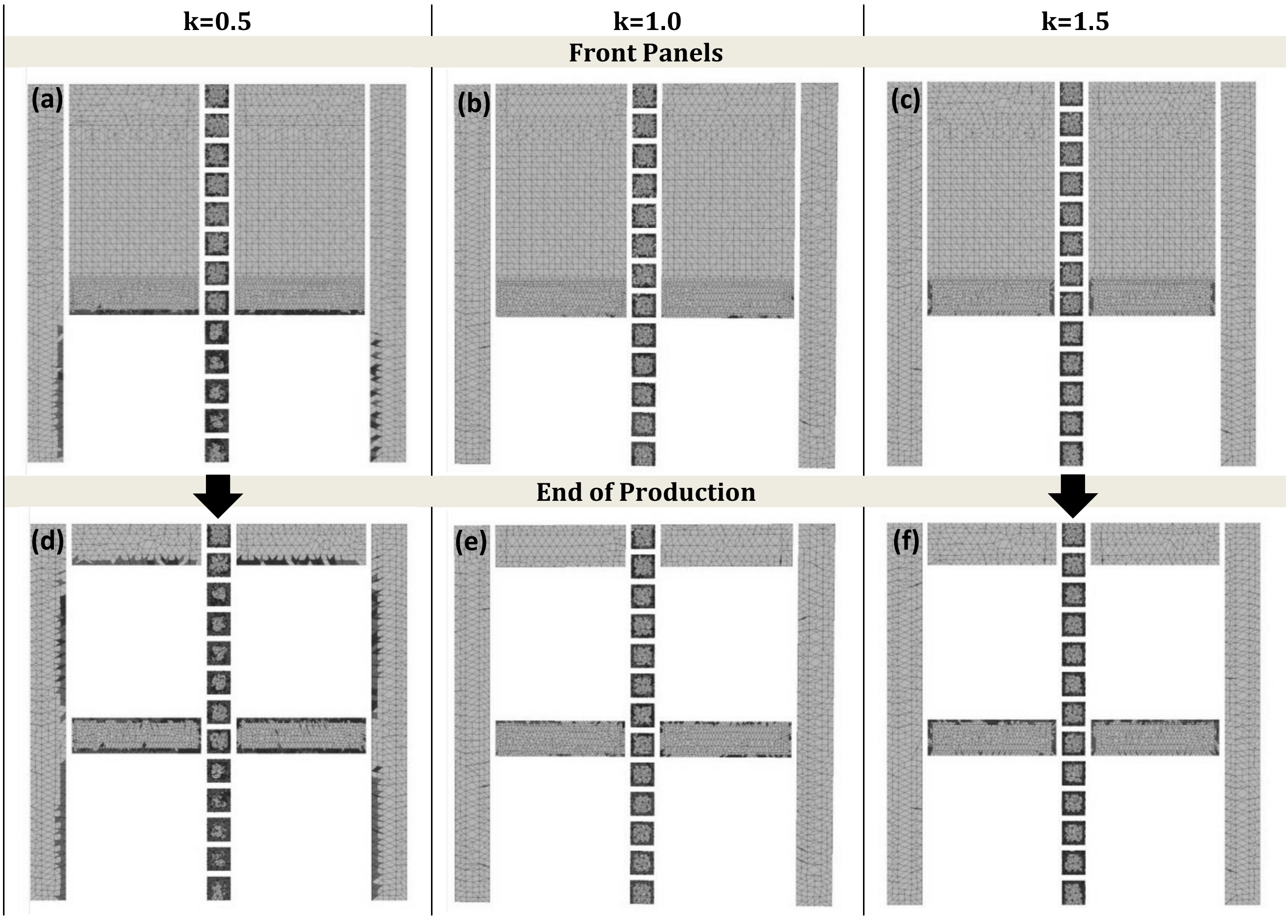

Figure 12. Yielded elements (dark colors) around longwall panels under different field stress conditions

In numerical analysis, it is known that stress distribution and post-failure deformations are directly related to the material model. Previous studies in the literature based on continuum analyses confirm that the advance of caving in longwall mines simulated with the strain-softening model provides more realistic simulation outputs compared to the elastic and elastic-perfectly plastic models (Vakili et al., 2010). In this study, additional analyzes using the Mohr-Coulomb strain-softening model were carried out using discontinuous media in order to examine the effects of the material model on the stress distribution inside pillars. The residual material properties operating in the post-failure stage were reduced to one third of the peak strength parameters and the production in the first two panels was simulated (Figure 13). Compared to the pillar loadings in the perfectly-plastic material model (Figure 11), higher stresses were observed close to the free surfaces of pillars, which may indicate violent failure events.

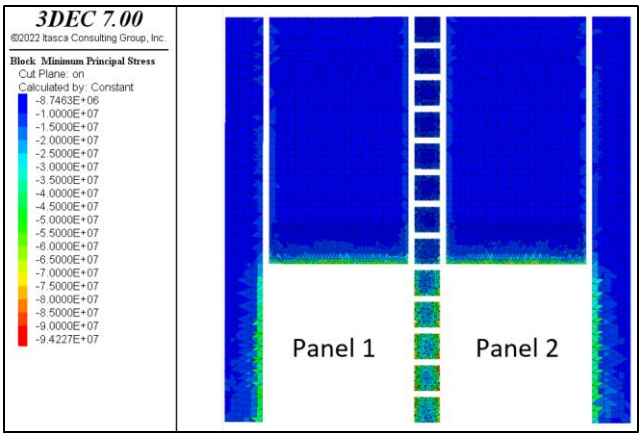

Figure 13. The maximum stress distributions around the longwall panels when strain-softening model is used, k=1 and pillars are square

Figure 14 shows the evolution of stresses at the midpoints of the first, fifth, eighth and eleventh pillars following production of the two panels in the front with a square pillar arrangement and using the strain-softening material model. Compared to the regular stress distribution observed in the pillar cross- section obtained with the perfectly plastic model, it was observed that the stresses increased around the free surfaces of the pillars and roadways when the strain softening model is used. At the center of the pillar, the stress concentrations were observed to be lower. It was concluded that the strain softening model suits better, compared to the perfectly plastic material model, for simulation of the induced stresses at the abutments of the roads and pillars, which develops parallel to the progress on the coal face.

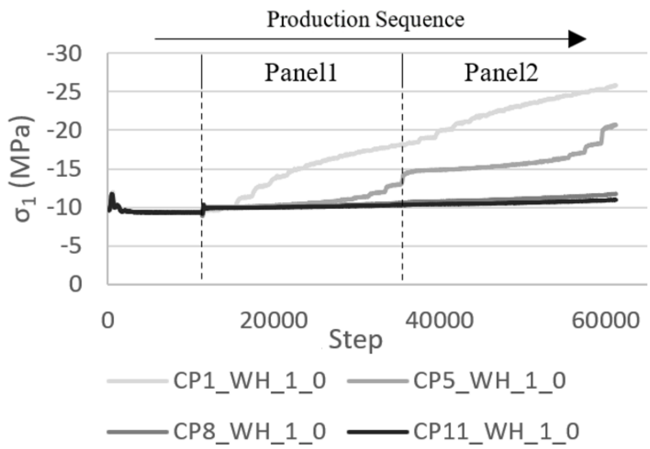

Figure 14. The maximum principal stress histories on pillars of the longwall model when strain-softening model is used, k=1 and pillars are square

Figure 15 shows the maximum principal stress contours on the barrier pillars when k=1. The end of production in the front panels (a) and all panels (b) sequences both point out the abutment pressures around the outer surfaces of barrier pillars. Compared to the center of the pillar, stress concentrations increase through the outwards. The simulation outputs imply that the barrier pillars are necessary for the main road stability.

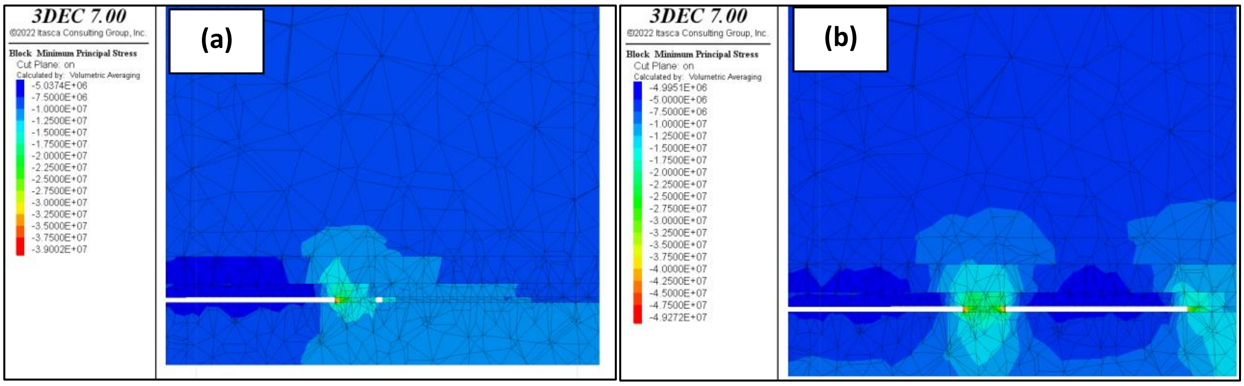

Figure 15. When k=1 the maximum principal stress contours on the barrier pillars for (a) the end of front panels, and (b) the end of all panels

Finally, the simulation results should be regarded to be dependent on the model input parameters and the boundary conditions. Although the presented study covers a common case, simulation results may significantly alter due to the differences in material characteristics of different types of coal, the depth, the surrounding strata, the structural geology and the seismic potential of the field. The parametric study intended to provide an understanding about the effects of field stress conditions when k=0.5, k=1.0, k=1.5 and different pillar width to length ratio. Most of the simulation outputs were presented for k=1.0 for practical reasons. However, there are several mechanical and geometrical parameters controlling the stress distribution. Although it is not possible to cover every potential case, the common parameter sets would be subject to follow up studies.

6. Conclusion

Numerical simulation outputs showed that production of multiple longwall panels in a large coal seam can result in stress concentration on the pillars nearly 4 times the before production state. The most critical pillars are the ones where the longwall retreat begins. Excavation related stress concentrations may cause pillar failure, as well as triggering the pillar burst, which is a dynamic type of failure due to excessive stress accumulation. Rectangular pillar arrangement can be said to be effective in reducing the stresses despite the increasing loss of coal due to the relatively large pillar cross-section area. However, it is useful in terms of mitigating dynamic failures. It was found that when the horizontal field stresses are higher than the vertical stresses, the stress concentrations on the pillar where the longwall retreat begins are not significantly different compared to the case of equal field stresses. Another study outcome is that the stress distribution on the pillar cross-section increases outward from the center and may cause pillar bursts in brittle rocks such as hard coal. At this point, it was determined that the material model used in the numerical analysis is important, especially the simulation of the abutment pressures using the strain-softening model provides better results. Finally, it can be concluded that the sustainable application of the longwall method, which provides the advantages of production speed, quantity and cost in underground coal mining, is possible by properly planning the panel layout, pillar dimensions and considering the geomechanical inputs.

Conflict of Interest

No conflict of interest was declared by the authors.

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