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Research Article

Development of geomechanical model for determination of elastic modulus and study on law of caving span induced by mechanized longwall mining

Pham Van Chung[1], Nguyen Quoc Long[1,4]*, Nguyen Dinh Huy[2], Dinh Thanh Tuan[3], Luu Van Huyen[5]

[1] Hanoi University of Mining and Geology, Hanoi, Vietnam; phamvanchung@humg.edu.vn
[2] Hanoi University of Civil Engineering, Hanoi, Vietnam; huynd@huce.edu.vn;
[3] Dong Hai Measurement Company Limited, My Tho City; ktbddonghai@gmail.com
[4] Innovations for Sustainable and Responsible Mining, Hanoi University of Mining and Geology, Hanoi, Vietnam; nguyenquoclong@humg.edu.vn
[5] Hanoi University of Natural Resources and Environment; lvhuyen@hunre.edu.vn

* Corresponding author: nguyenquoclong@humg.edu.vn; Tel.: +84–916196336

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Abstract: A geomechanical model is developed to determine the elastic modulus, to analyze the rules of rock and surface displacement, and study the caving span caused by mechanized longwall mining. The rules of rock deformation and displacement have been determined, including the stress distribution, the development of the failure zone, the height of the failure zone, the caving span of the longwall, the order of layer arrangement, the displacement deformation vector, the maximum subsidence, and the boundary displacement angle. In this paper, the author uses the Rocdata program to determine the elastic modulus (E), cohesion (C), and internal friction angle (φ) as inputs for the geomechanical model. The software RS2 (Phase 2) from Rocscience Inc. (Canada) is then used to calculate some parameters and displacement quantities. The results showed that the maximum subsidence in the dip direction is $\eta = -2.250$ m and in the strike direction $\eta = -0.659$ m. The boundary displacement angle is $\beta_0 = 47°$. The caving height is H = 10 m. The caving repeats at the span 10th, meaning that the length of the longwall mined in the strike direction reaches 65 m. Afterward, the caving span and the height of the caving zone repeat.

Keywords: Deformation and displacement; Geomechanical model; Elastic modulus; Caving span of the longwall.

1. Introduction

Various methods have been used to study rock deformation and displacement. This includes theoretical methods based on the finite element method to determine the stress-strain state from the geomechanical model. A geomechanical model is used to determine the deformation and displacement parameters as well as the complete destruction of the rock mass within the influence zone of the longwall [1]. During the process of stress redistribution in the rock mass, it can reach a completely stable state or an unstable state at different levels, which can cause a loss of force equilibrium, leading to the bending and collapse of roof strata [1, 2].

In Vietnam, studies on mine deformation are mainly conducted based on observation data [3–5], some recent studies have applied AI technology to predict surface subsidence [6, 7]. These studies show high reliability, but it can only be predicted after observation data is available, meaning that the subsidence process has occurred. To solve the problems, elastic and continuous environment modeling was used in the works of researchers [8–14]. Since 2011, several studies on deformation and displacement using equivalent material models have been done in various documents [15, 16–20], focusing on load-bearing capacity and deformation control in roadways [21]. However, these documents show that the research is labor-intensive and conducted on small models, resulting in a large equivalent coefficient. Theoretical research to predict subsidence has also been carried out by some experts. The study [19] used the Phase2 program to analyze subsidence and mechanical transformation during the combined underground and open-pit mining. The study [1] constructed a geomechanical model due to the impact of mechanized longwall mining in thick seams. The study determined a coefficient KC = 1.2 for the Quang Ninh coal region and found the deformation displacement rules. The prediction of the height of the failure zone and layer separation can be found in many studies [17, 22, 23].

In this paper, the author uses the Rocdata program to calculate the elastic modulus (E), cohesion (C), and internal friction angle (φ) as input data for the geomechanical model. The software RS2 (Phase 2) is then used to study the deformation and displacement rules and caving span of Seam I (12) at Mong Duong coal mine, Quang Ninh coal field, Vietnam.

2. Materials and Methods

2.1. Study area

Mong Duong coal mine is located in Mong Duong ward, Cam Pha City, Quang Ninh province, Vietnam. The exploration area is situated 10 km to the East-Northeast of Cam Pha city. At the mine, Seam I (12) is mined using the partially mechanized longwall mining method with full caving from level -97 to -45. The average depth from the surface to the mining longwalls is 90 m to 120 m. The coordinates of the research area limits are shown in Table 1.

Table 1. Coordinates of the research area limits.

No.	Point name	X	Y
1	H	29600	31200
2	E	29600	31900
3	F	30300	31900
4	I	31300	31200

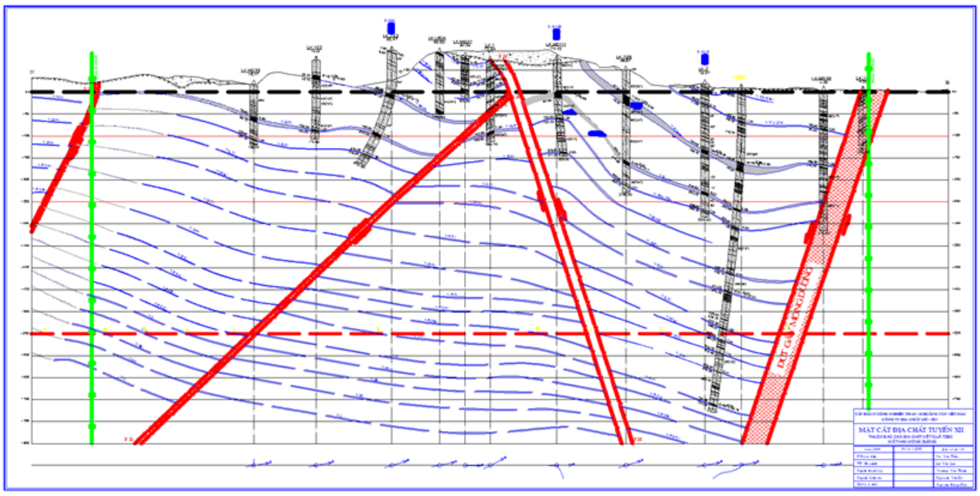

Figure 1. Geological cross-section of line XII [24].

The geological conditions of the seam I (12) are shown in Table 2. The geological line XII passing through the research area is illustrated in Figure 1.

Table 2. Geological conditions of seam I(12).

No.	Parameters of the longwall	m/degree	Seam I(12)
1	Mining level	m	-97 ÷ -45
2	Seam thickness	m	8
3	Seam dip angle	degree	40
4	Overburden thickness	m	5
5	Longwall length in the dip direction	m	60-70
6	Longwall length in strike direction	m	80-120
7	The average depth of the longwall	m	90-120

2.2. Calculation of Elastic Modulus for the Geomechanical Model of Mong Duong Coal Mine

During the geotechnical construction process, in addition to sampling at line XII, additional boreholes LK102, LK103, LK736, LK732, LK2, LK-L2, LK16, LK19, LK24 were taken. The compressive strength (σ) of sandstone ranges from 90 to 126 MPa, with an average of 113 MPa; siltstone ranges from 30 to 55 MPa, with an average of 42 MPa; claystone ranges from 17 to 40 MPa, with an average of 28 MPa; and coal has a strength of 17 MPa [25]. The Rocdata program is used to determine the elastic modulus (E), cohesion (C), and internal friction angle (φ) as shown in Table 3.

To calculate the deformation and displacement of the Mong Duong coal mine, it is necessary to study and build a geomechanical model. The author proposed the elastic modulus EC = KC.ER (where ER is the elastic modulus calculated from Rocdata, KC = 1.24) [1], while other parameters such as cohesion and internal friction angle remain unchanged. The results from RS2 with varying cohesion and internal friction angle show that the deformation does not change significantly in the model. Thus, the determined input parameters E, C, φ for running the geomechanical model of the Mong Duong coal mine are shown in Table 4.

Table 3. Geological conditions of seam I(12).

No.	Type of rock	Compressive strength σ (MPa)	Geological Strength Index (GSI)	Blast damage factor (D)	Material constant (mi)	Elastic modulus E (MPa)	Cohesion C (MPa)	Internal friction angle Φ (dg)
1	Sandstone	113	45	0.8	17	2110	0.805	42.358
2	Siltstone	42	37	0.8	7	691	0.323	23.276
3	Shale	28	11	0.8	4	244	0.40	12.281
4	Coal	17	8	0.8	4	93	0.052	3.5

Table 4. E, C, φ for Mong Duong coal mine.

No.	Parameters	Sandstone	Siltstone	Shale	Coal
1	EC	2532	829.2	292.8	93
2	C	42.358	23.276	12.281	3.50
3	φ	0.805	0.323	0.40	0.052

3. Results

3.1. Calculation diagram

Applying the above geomechanical model, the input parameters E (elastic modulus), C, and φ are entered into the software RS2. The author takes the cross-section of line XII as a representative cross-section for specific calculations. The rock layers are considered to be parallel to each other. The stratigraphy of the rock includes sandstone, siltstone, shale, and coal. The calculation domain of the model has a width and height of 700×300 m compared to the actual width of the cross-section of 1400×450 m. It should be noted that the area from the observation station of seam I (12) to the outer boundary is 500 m, and the mining level of seam I (12) from -80 to the surface is 250 m, meaning a height of about 330 m. The modeled dimensions of 700×300 m are reasonable compared to reality and are shown in Figure 2.

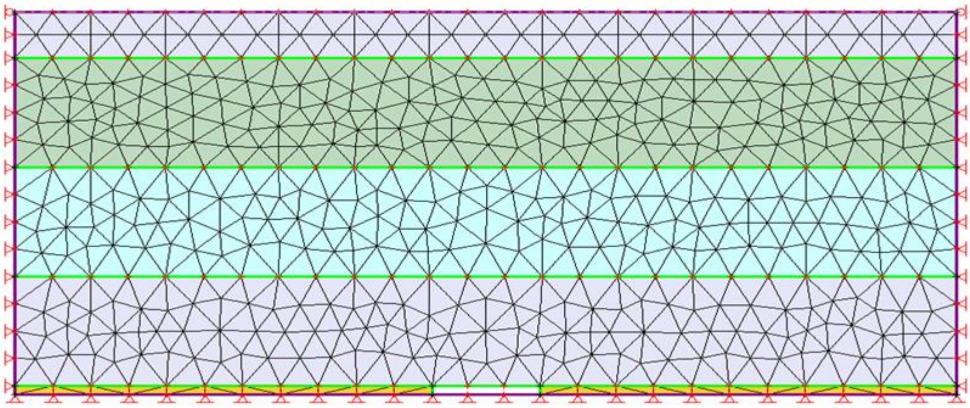

Figure 2. Simulation of soil and rock strata and model dimensions.

3.2. Calculation of deformation and displacement

The longwall mining system uses hydraulic supports. The roof control is managed by full caving, with a coal seam thickness of 8 meters and a longwall length of 80 m. The parameters for sandstone, siltstone, shale, and coal are entered into the model as shown in Figure 3.

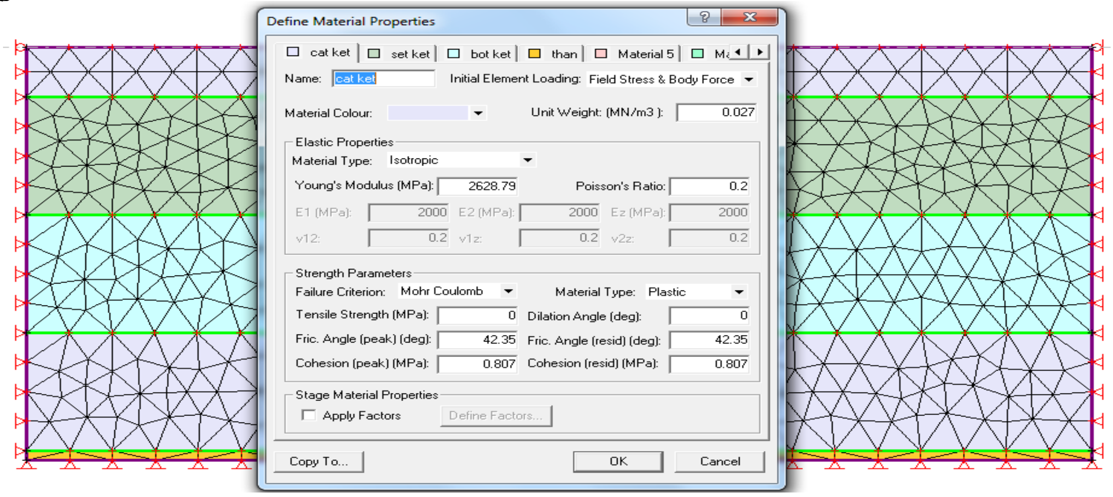

Figure 3. Entering parameters of the model.

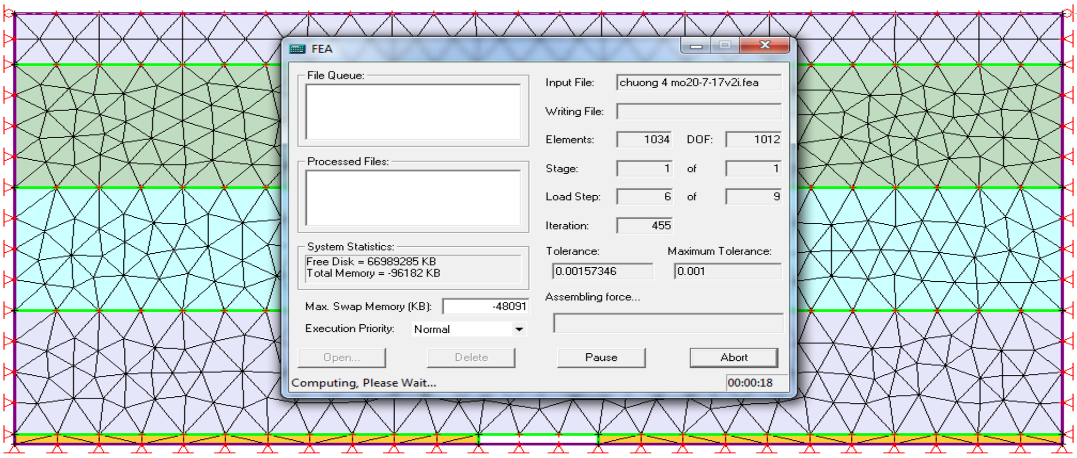

Figure 4. Computing the displacement.

After entering the parameters, the software automatically runs the calculation loop for deformation displacement, as shown in Figure 4. The vertical and horizontal displacements are shown in Figures 5, 6.

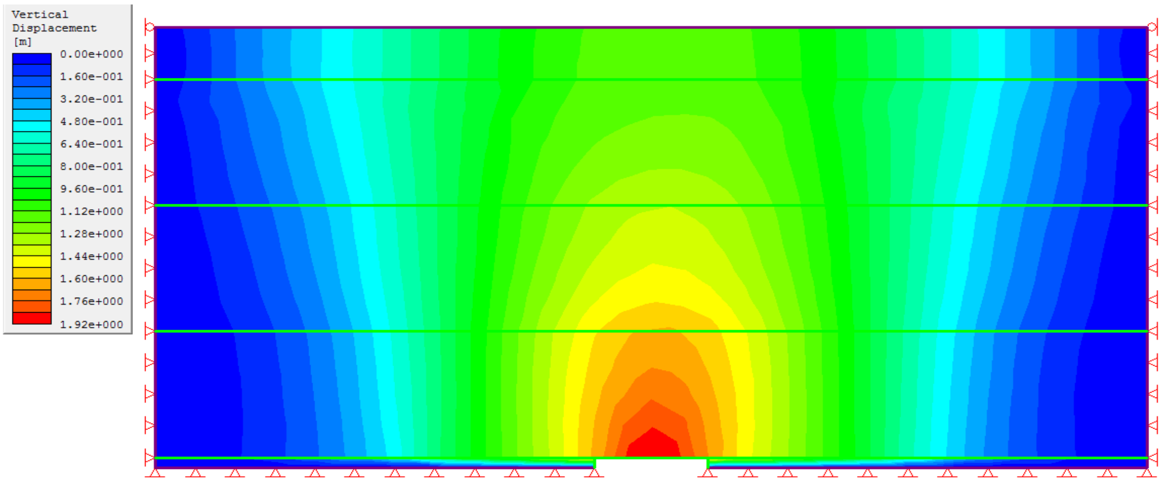

Figure 5. The vertical displacement of rock layers due to underground mining.

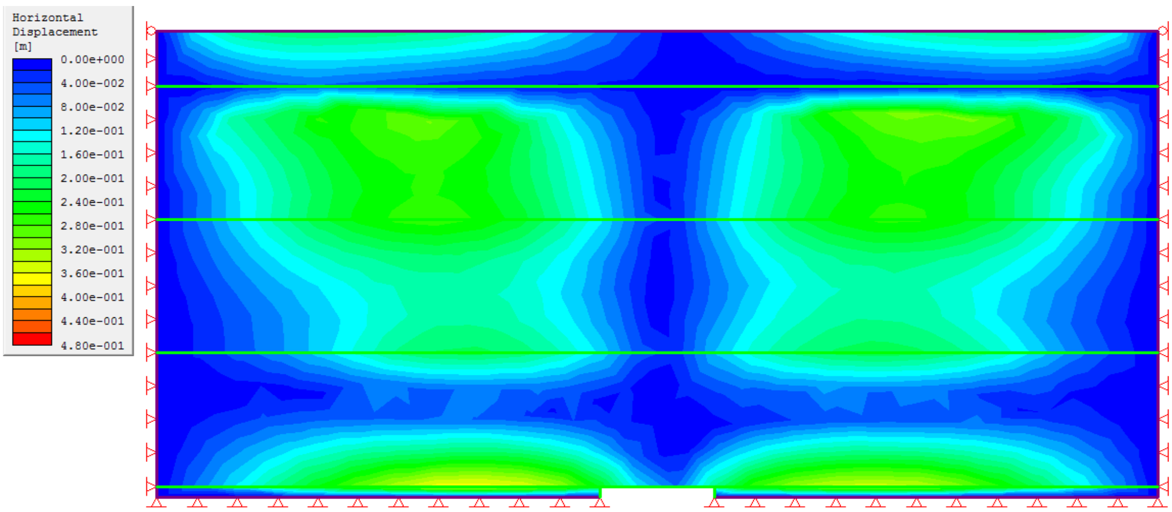

Figure 6. Horizontal deformation.

The determination of subsidence and displacement angle is shown in Figure 7. The graph describing the displacement process of each rock layer is shown in Figure 8.

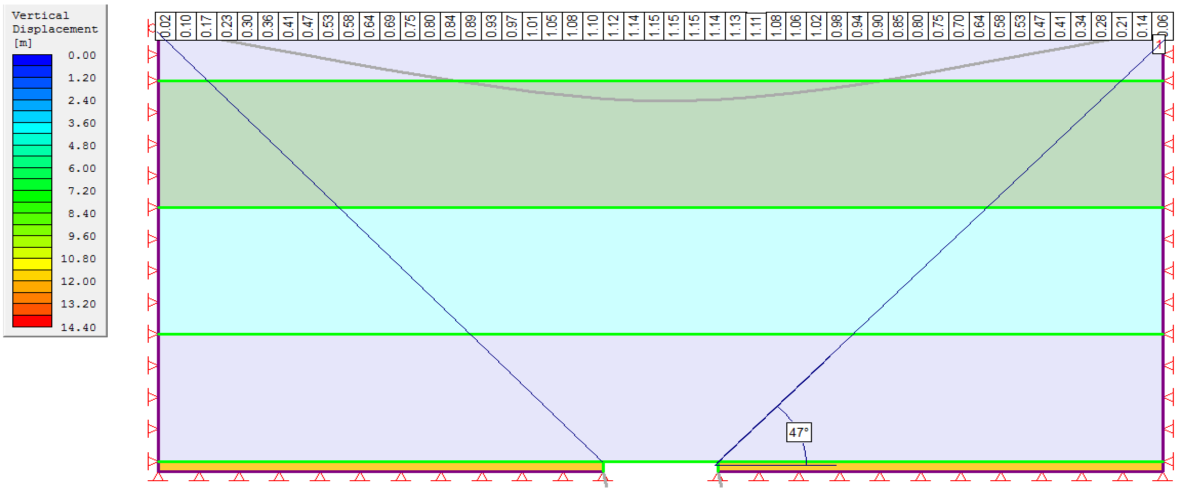

Figure 7. Vertical displacement and displacement angle.

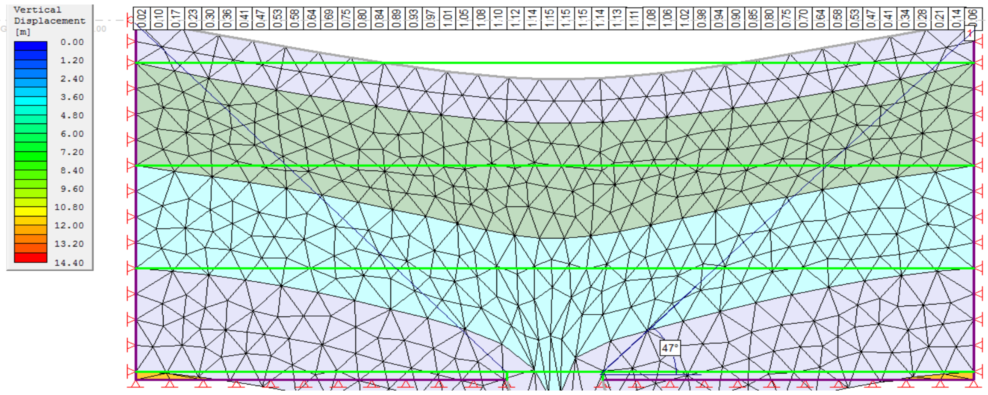

Figure 8. Simulation of displacement of rock layers.

The displacement vectors in the rock layers and the distribution of finite elements in the model are shown in Figures 9 and 10, respectively.

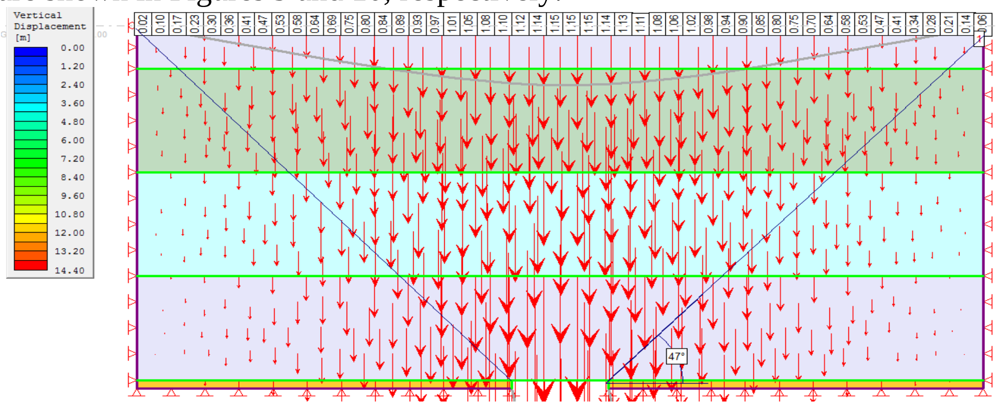

Figure 9. The displacement vectors in the rock layers.

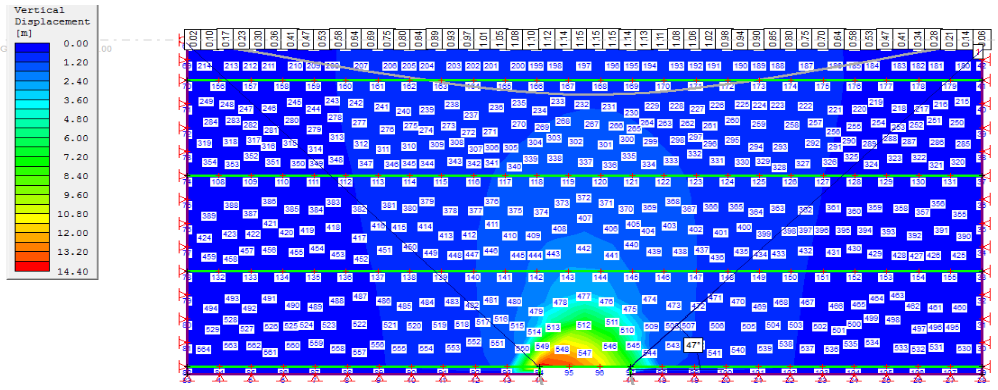

Figure 10. The distribution of finite elements in the model.

3.3. Determination of the caving span of the mechanized longwall I (12)

Calculating the stress-strain state for a mining cycle in the mechanized longwall along the main dip direction is a problem of determining the displacement pattern of the roof coal seam and the overlying strata along the roadway. The displacement of the rock layers due to coal mining originates from the manifestation of mine pressure and abutment pressure in longwall mining. The displacement span of the longwall and the distribution of abutment pressure ahead and behind the longwall face are shown in Figure 11.

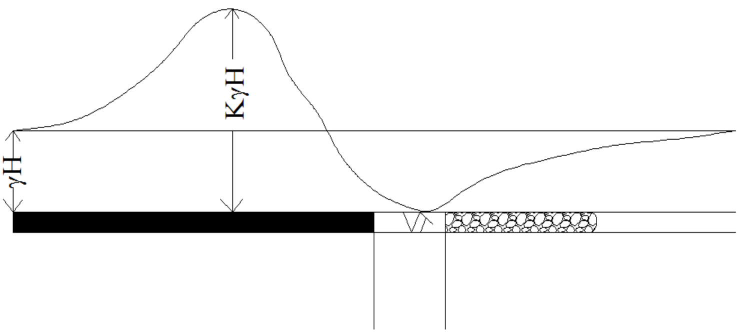

Figure 11. Distribution of abutment pressure ahead and bedind the longwall face.

In the direction of longwall mining, the destruction of the overlying strata gradually develops forward. The process of stress-strain redistribution in the rock strata above the longwall continuously occurs. By analyzing the stress-strain of the rock and coal blocks above the longwall, we can obtain a picture of the destruction (plastic deformation), thereby calculating the caving height (i.e., the height at which the rock strata become plastic - the shear strength reaches residual deformation). The mechanized longwall extracts an 8 m thick seam along the dip direction. The area prepared for installing the support frame is a roadway approximately 6 m wide. Each face advance in each coal-cutting cycle is 0.63 m. The coal cutting height is 2.4 m, followed by full caving of the top coal. The calculation diagram is shown in Figure 12. The physical and mechanical properties of the rock layers are taken according to Table 3. The initial face advance distance is 12.3 m (including 10 caving spans of the longwall and the distance for preparing the support frame installation). To clearly show the stress-strain zone, the author considers 10 mining cycles 6.3 m as one span on the model with 20 spans of the longwall advance to find the distribution pattern of the displacement and deformation zones around the longwall and on the ground surface. The finite element method is applied using the RS2 (Phase 2) software from Rocscience Inc. (Canada).

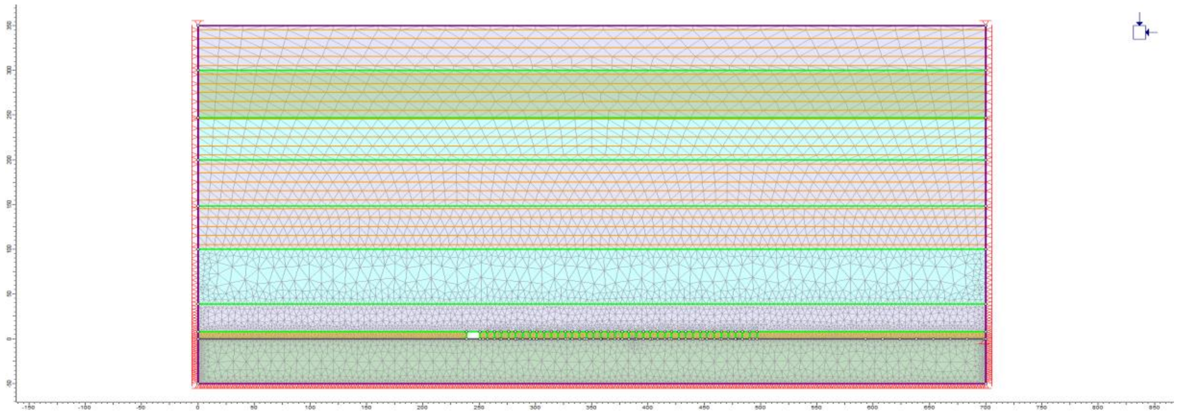

Figure 12. Geomechanical model of the mechanized longwall along the strike direction.

The calculation results of the maximum principal stress values in the caving spans of the longwall mining are shown in Figures 13 to 19.

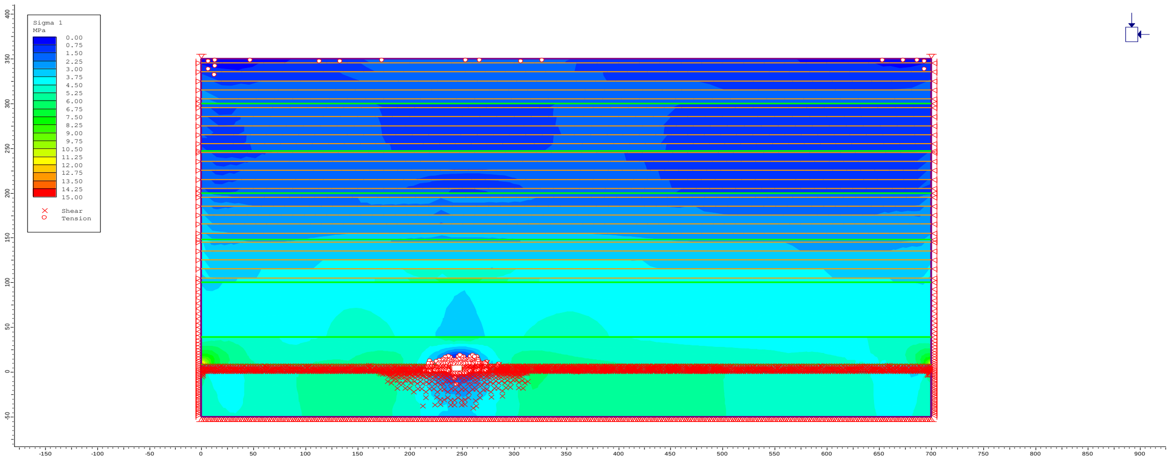

Figure 13. Description of the principal stress σ_1 at the initial longwall.

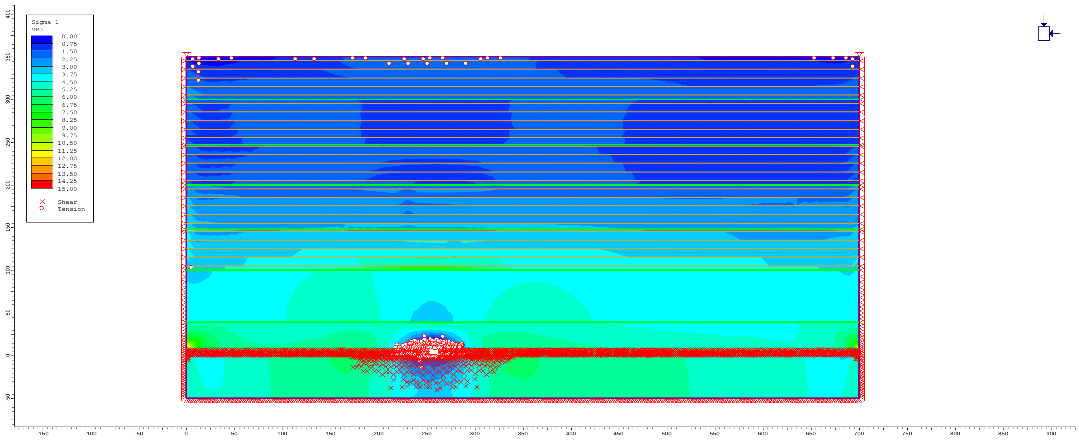

Figure 14. Description of the principal stress σ_1 at the 2nd span.

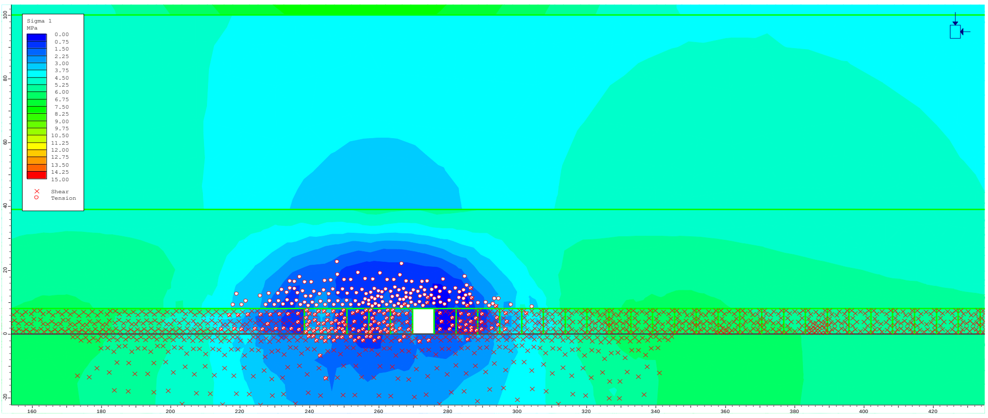

Figure 15. Description of the principal stress σ_1 at the 5th span.

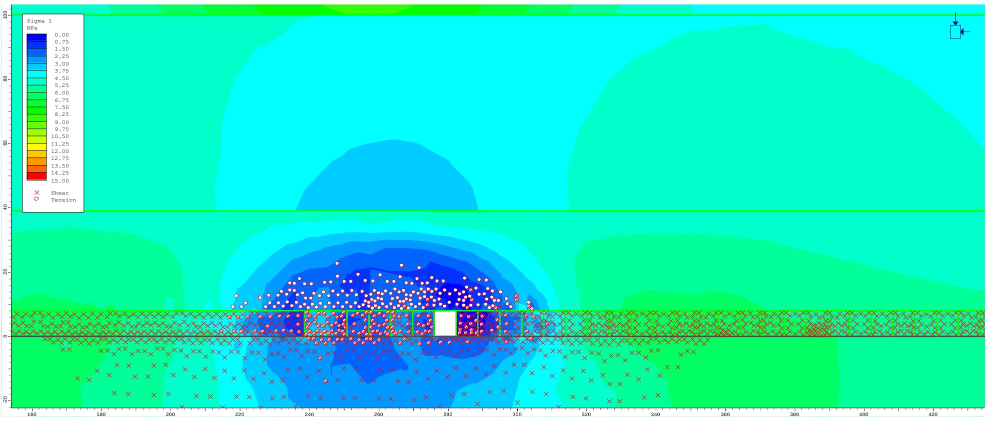

Figure 16. Description of the principal stress σ_1 at the 6th span.

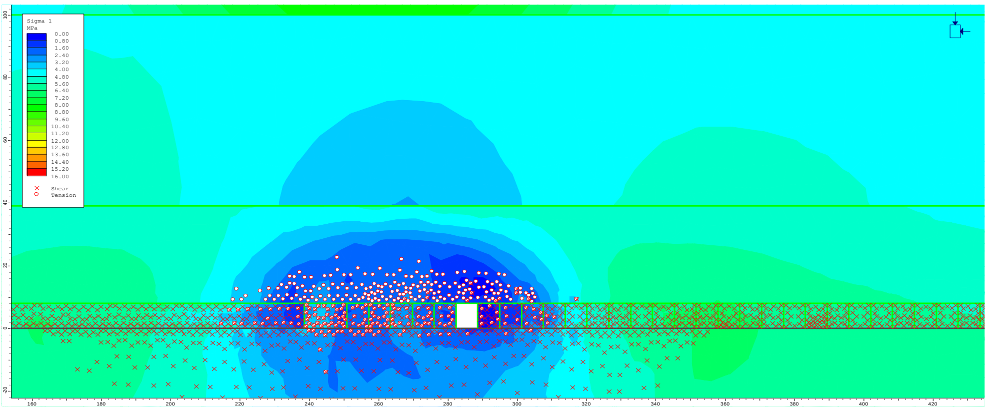

Figure 17. Description of the principal stress σ_1 at the 7th span.

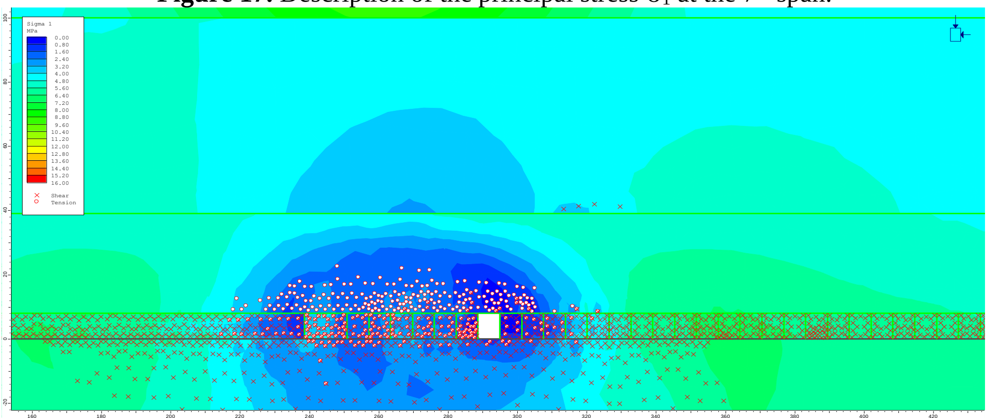

Figure 18. Description of the principal stress σ_1 at the 8th span.

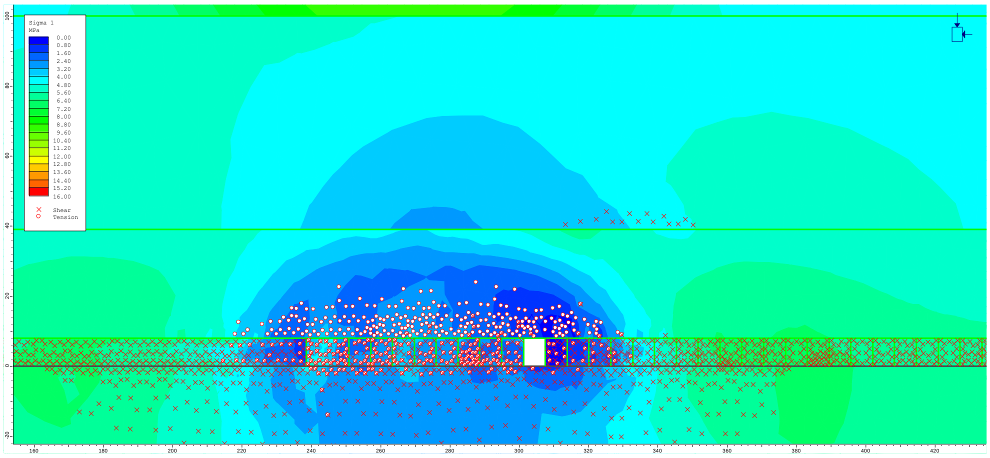

Figure 19. Description of the principal stress σ_1 at the 10th span.

Through the simulations in the above figures, it can be seen that after the face advance, the destruction describes the caving of the rock layers above the longwall. From the figures, the caving height (the distribution area of the circular points) is calculated to be H = 10 m. Thus, at the 10th span, the caving span repeats. This means that the length of the longwall mined along the strike direction reaches 65m, and the caving span and height repeat.

Summarizing the face advances with 10 spans, we see that at the 10th span, the distribution pattern of the principal stress σ_1 returns to the initial state as shown in Figure 20.

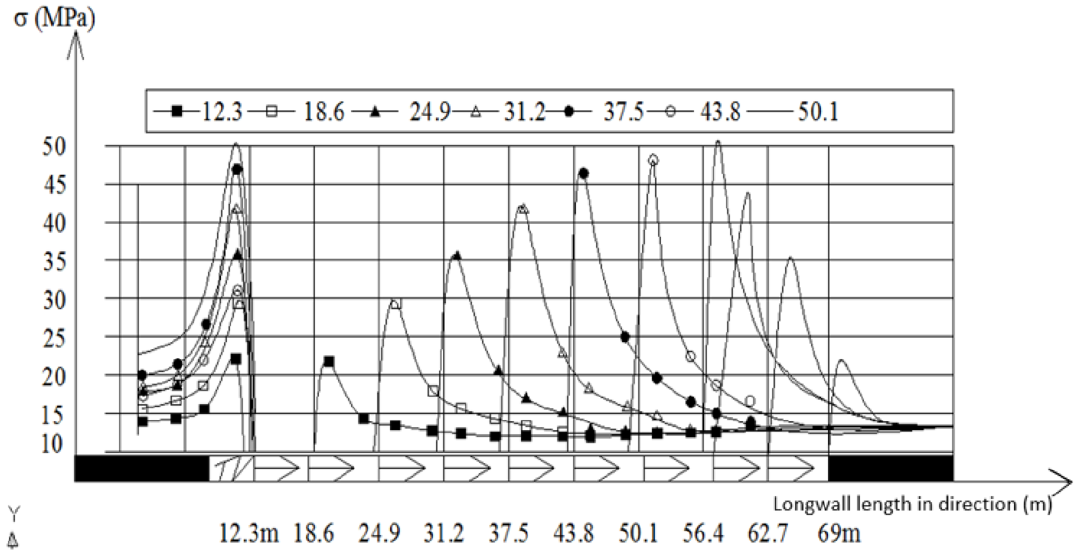

Figure 20. Distribution pattern of the principal stress σ_1 at the spans.

The calculation results of the displacement and deformation of the rock layers on the ground surface and above the longwall are shown in Figures 21–24.

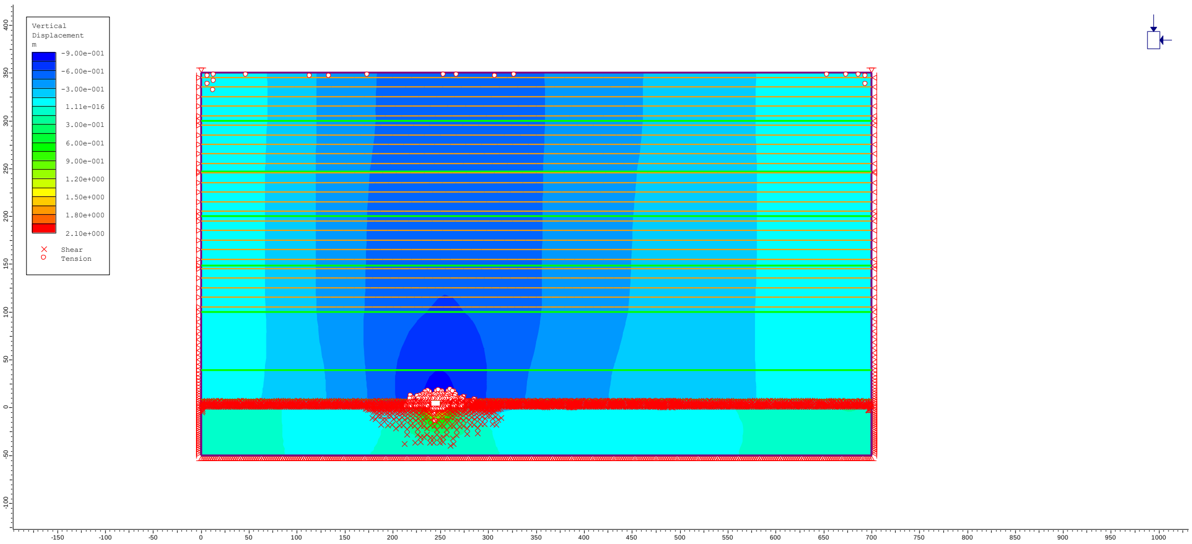

Figure 21. Displacement and deformation of the rock layers during initial longwall mining

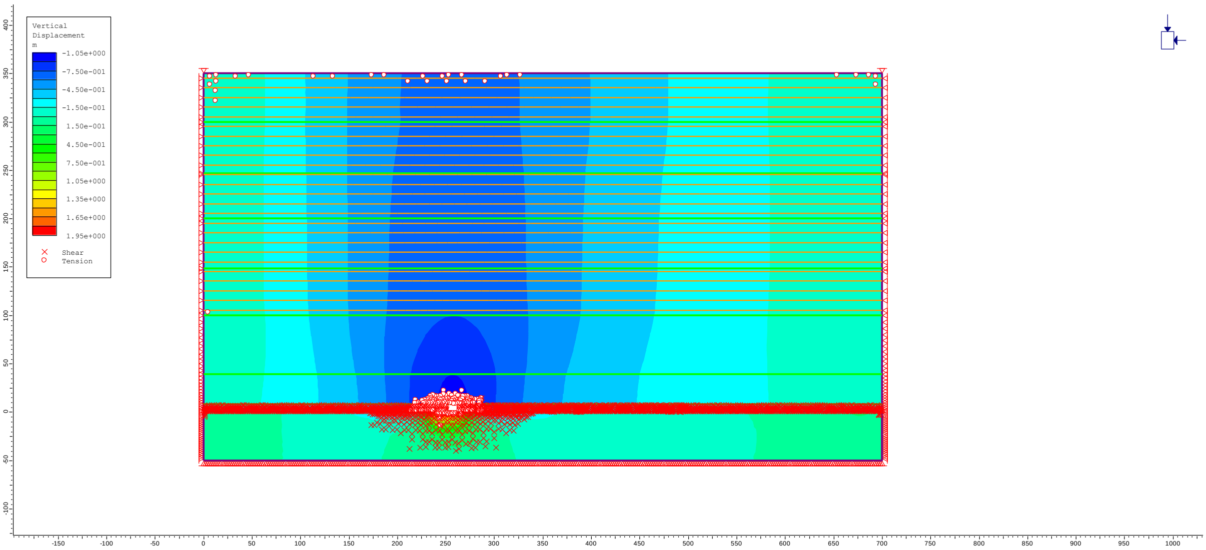

Figure 22. Displacement and deformation of the rock layers at the 5th span.

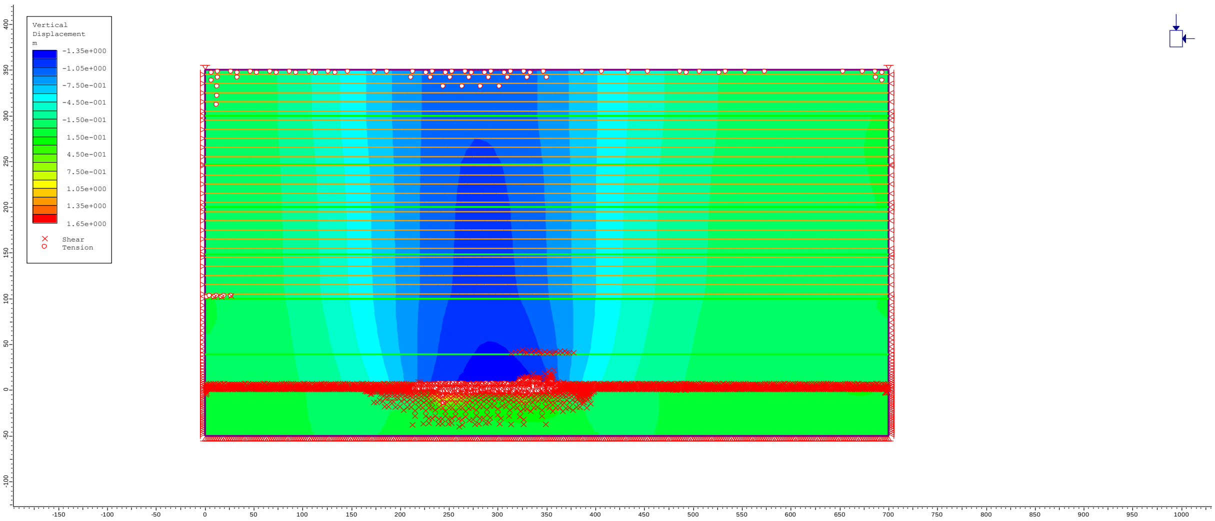

Figure 23. Displacement and deformation of the rock layers at the 10th span.

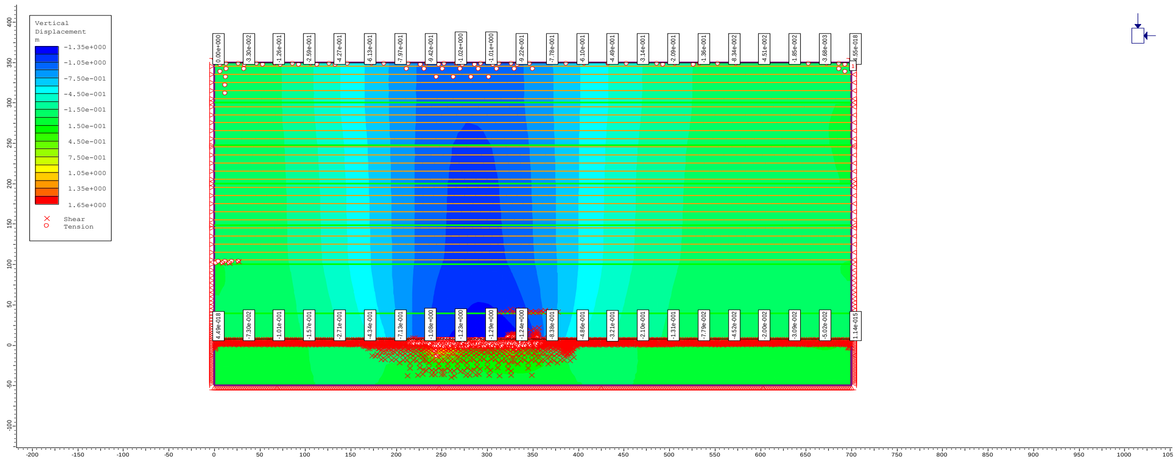

Figure 24. Displacement and deformation on the ground surface and basal rock layer.

The vertical displacement is shown in the cross-section as in Figure 25.

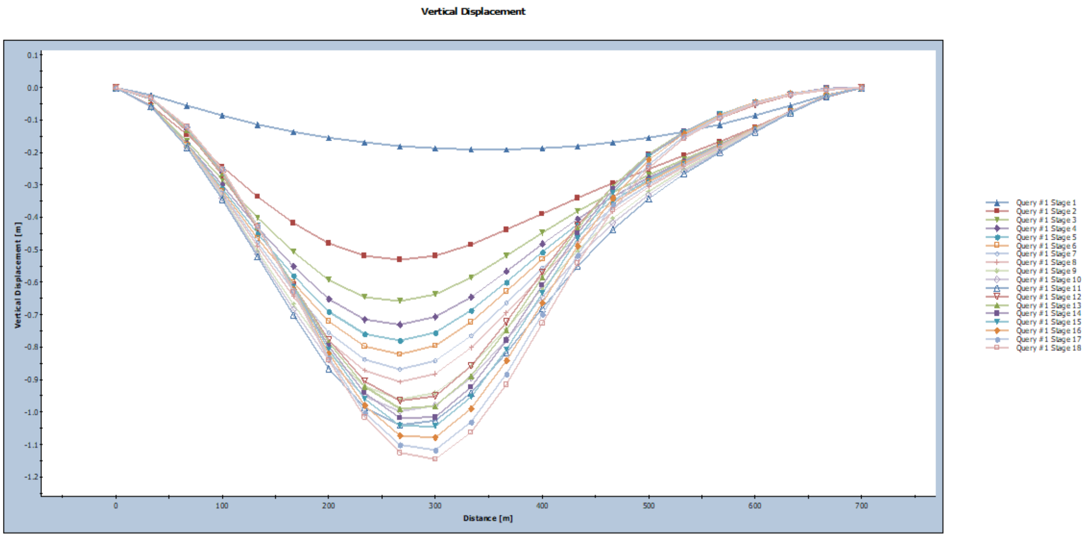

Figure 25. Vertical displacement values on the surface.

The vertical displacement of the surface above the longwall roof is shown in Figure 26.

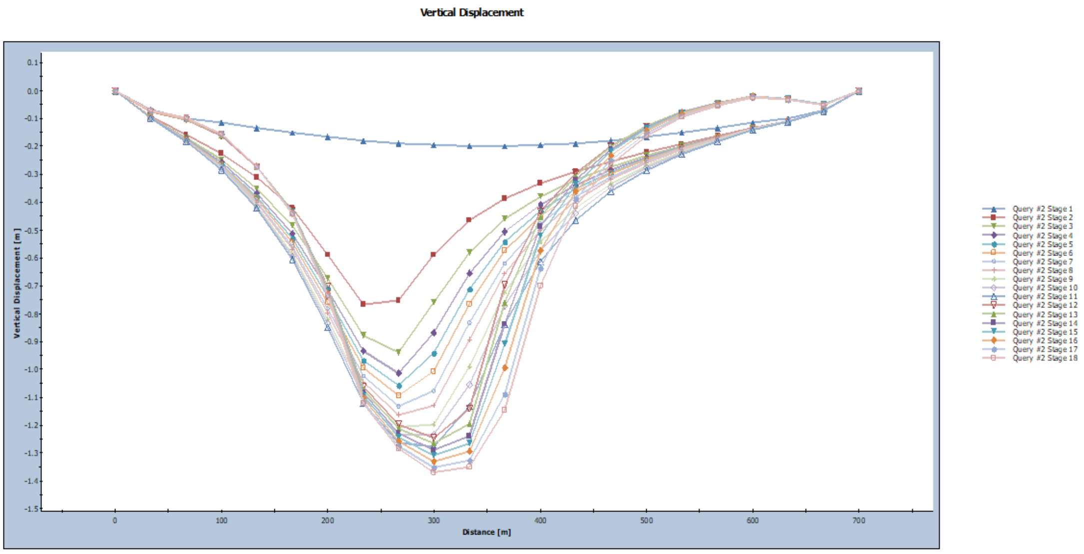

Figure 26. Subsidence curve above the longwall roof.

3.4. Analysis of the geomechanical model

The surface subsidence is shown with the red line representing the maximum value and the blue line representing the minimum value (Figure 5). The calculation result determines the maximum subsidence η = 1.150 m, with the boundary displacement angle $\beta_0 = 47^o$ (Figure 7).

The results analyzing surface subsidence are shown through the deformation of the finite element mesh (Figures 7, 8). This indicates that when mining at a certain depth, the subsidence area on the surface expands, but the curvature decreases. This means that the deeper the mining is, the less likely it is to cause sliding and collapsing of architectural structures. This also demonstrates that as mining goes deeper and reaches a safe mining depth, the displacement and deformation do not propagate to the surface.

The displacement and deformation of the rock layers show three distinct zones: the complete displacement zone near the roof forming a V-shape, above which is the sagging zone, and the compressed rock zone (Figure 7).

The displacement vector direction is shown, with the vector magnitude increasing from the surface down to the longwall roof, reaching a maximum value at the longwall roof. The further from the center of the longwall, the smaller the displacement vector value is, indicating the compressed rock zone (Figure 9).

The finite elements in the model are uniformly distributed and arranged according to a certain pattern. The destruction zone mainly develops above the roof of the mining area, with the height and shape depending on the dip and the relative distance of the mining area to the surface. It is also noted that during mining, destruction zones may appear on the surface due to overall subsidence and deformation. The tensile failure may appear on the upper boundary of the study area (Figure 10).

The caving height (the distribution area of the circular points) is calculated to be H = 10 m. Thus, at the 10^{th} span, the caving span repeats, meaning that the length of the longwall mined along the strike direction reaches 65 m, and the caving span and height repeat (Figure 20).

Therefore, to ensure the accuracy and reliability of the results from the geomechanical model, the paper determines the maximum subsidence on the model and verifies against the monitoring results at the Mong Duong coal mine, as shown in Table 5. The verification results show that the angle and displacement from the geomechanical model are very close to the actual value.

Table 5. Comparison of subsidence and displacement angle.

Value	Geomechanical model	Field measurement	Note
η	-2.250 m	-2.282 m	Dip direction
η	-0.659 m	-670 m	Strike direction
β_0	47^o	45^o	

4. Conclusion

The geomechanical model accurately determines displacement and deformation parameters at the Nam Mau coal, showing close agreement between field observation and the calculated values for displacement and other parameters.

The model's calculations for the longwall along the dip direction reveal variations in the rock layers surrounding the longwall, including specific strata and surface conditions. The boundary displacement angle was determined to be $\beta_0 = 47^o$, with maximum subsidence values of η = −2.250 m in the dip direction, and η = −0.659 m in the strike direction. The caving height was found to be H = 10 m, along with the caving span of the roof rock in thick seams mined using mechanized longwall methods. The model identifies their zone: the continuous sagging zone, the sagging zone with cracks, and the displacement basin on the surface.

Overall, the geomechanical model provides a comprehensive view of the displacement and deformation processes in rock strata and ground surfaces.

Author contribution statement: Generating the research idea; statement of the research problem; analysis of research results and data preparation; wrote the draft manuscript: P.V.C., N.D.H.; Analyzed and interpreted the data, wrote the draft manuscript: L.Q.N., D.T.T., L.V.H.

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Competing interest statement: The authors declare no conflict of interest.

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