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Research Article

Analysis of borehole stratigraphy combined geomechanical model with field monitoring methods to determine displacement angles in Seam I (12) of the Mong Duong coal mine

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Abstract: This study determines displacement angles in Seam I (12) of the Mong Duong coal mine using an integrated approach combining borehole stratigraphy, mechanical modeling, and field monitoring. Key parameters, including geological conditions, compressive and tensile strength, and internal friction angle, were analyzed to estimate displacement angles using the similar region theory. A geomechanical model incorporating elastic modulus, geological strength indices, and cohesion force was developed to calculate displacement and deformation angles. Surface monitoring station provided real-time field data for validation. The results show that the displacement angles of β = 42° from field data, β = 47°from the geomechanical model, and β = 50° from borehole analysis. These findings offer valuable insights for improving mining safety and optimizing underground operations in similar geological conditions. The combination of methods shows the best effect for mines without monitoring stations, the borehole stratigraphic analysis method can be applied and then the same area method can be applied to determine the deformation displacement angle for safe and effective exploitation

Keywords: Deformation and displacement; Geomechanical model; Elastic modulus; Monitoring Methods.

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1. Introduction

Displacement and deformation processes of rock and soil have been widely studied to enhance methods for assessing structural impacts caused by underground mining activities. Physical models with equivalent materials have proven valuable for understanding these processes, providing insights into deformation and damage mechanisms [1]. Despite extensive global research, field studies on displacement parameters in Vietnamese coal mines remain limited. This gap poses significant challenges for ensuring safety and optimizing mining operations in complex geological settings.

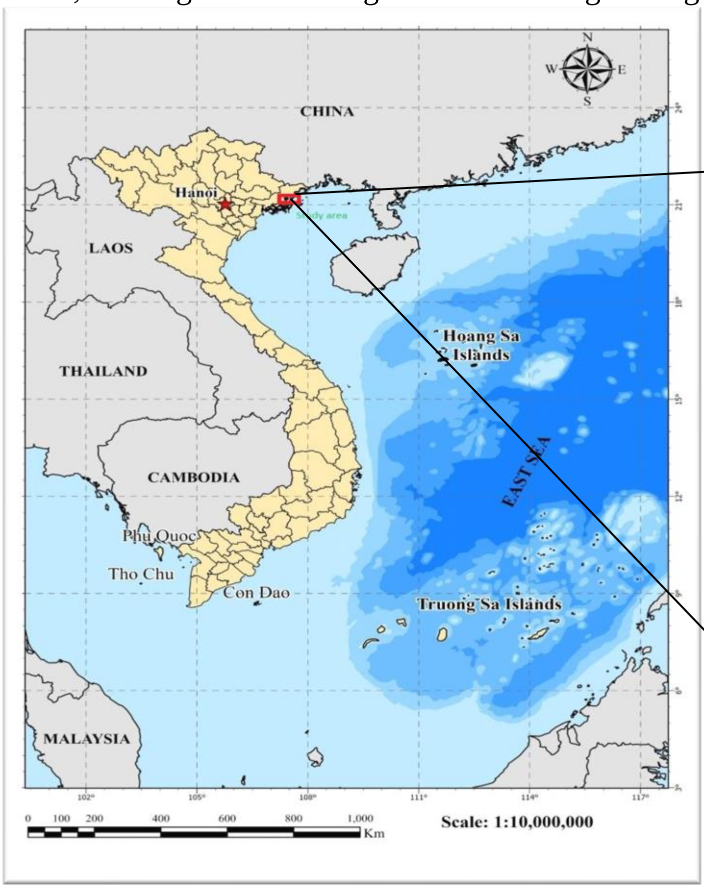
To solve this problem, in Vietnam, there have been many studies on deformation displacement due to the influence of underground and open-pit mining. These research methods are singular, there is no combination of complementary methods to solve the overall problem. Specifically: In 1980, the study [2] was the first person to lay the foundation for the study of soil and rock displacement and deformation due to underground mining in Vietnam. The author studied the displacement of soil and rock in the mass tectonic fault zone on 5 thin models with materials equivalent to the distance between small faults. In 2003, the study [3] has built a software program to effectively serve the processing of displacement and deformation monitoring data in the underground mining area.

From 2002 to 2007, the Institute of Mining Science and Technology - TKV built monitoring stations to determine displacement parameters and displacement quantities in order to recalculate the coal protection pillars for works on the land surface for the state-level project in charge and implementation [4]. In 2018, the study [5] has built research and development of geomechanical variation model the area of the motorized market furnace exploits thick pavements in some quang ninh underground coal mine.

In Vietnam, so far, there are only a few research works to predict ground displacement and deformation due to the influence of pit mining by the equivalent material modeling method [2], Institute of Mining Science and Technology - TKV and Department of Geodesy. The Institute of Mining Science and Technology has built monitoring stations to determine the displacement angles. This is a very valuable initial result, but there are still limitations, such as: it is impossible to create a similarity in the physical and mechanical indicators between the model and reality, the ratio of the model is too small compared to the actual range, and the results obtained are only qualitatively significant, cannot be obtained quantitatively [5].

The Quang Ninh coal basin, a major industrial reserve in Vietnam, is characterized by diverse seam inclinations and complex geological conditions, including folds and faults [6]. Within this basin, the Mong Duong coal mine features steep mountainous terrain with elevations ranging from 1 to 250 meters, intersected by streams and residential areas [7]. Underground mining activities in this region disturb the natural stress equilibrium, leading to displacement and deformation of rock layers and coal seams. These disruptions pose risks to surface structures and require a thorough understanding of displacement mechanisms [8]. Some studies on displacement and surface deformation due to underground mining in Quang Ninh can be mentioned as [9–16].

This study focuses on determining displacement parameters in Seam I (12) of the Mong Duong coal mine. By integrating borehole stratigraphy, geomechanical modeling, and field monitoring, this research addresses the lack of comprehensive studies in Vietnamese coal mines, offering valuable insights for enhancing mining safety and efficiency.



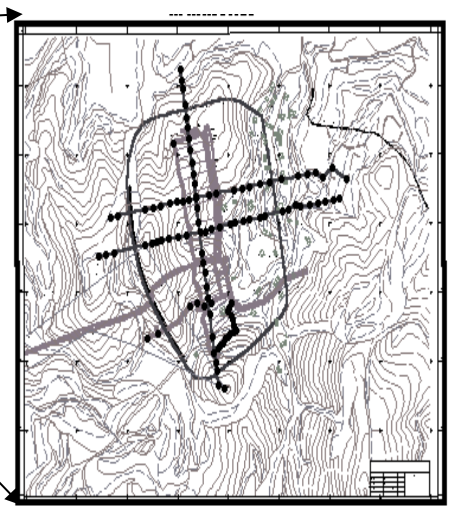


Figure 1. Location of deformation displacement monitoring station.

In this study, the study area is selected in the mining infrastructure of Mong Duong Coal Joint Stock Company, Vietnam (Figure 1). Mong Duong is an underground coal mine with a surface monitoring station.

2. Materials and Methodology

2.1. Determining displacement parameters

The displacement and deformation of rock and soil surfaces form the basis for selecting protective measures and conducting rational mining in areas that affect protected objects. In the former Soviet Union's coal mining industry, methods for estimating rock and soil displacement and deformation were based on experimental results [17, 18].

In the Quang Ninh coal basin, the study of rock and soil displacement and deformation has not been fully conducted. Therefore, when conducting underground coal mining, it is necessary to preliminarily determine the displacement angles to ensure safety and efficient mining. Both globally and in Vietnam, the method of analyzing borehole stratigraphy (similar region method) in Seam I (12) has been applied as a basis for determining initial displacement parameters for unexplored areas.

2.2. Determining displacement parameters through borehole stratigraphy analysis

Through the analysis of boreholes 726 and borehole 2 on line XII passing through Seam I (12) (Figure 2), rock sample tests were conducted to determine the hardness of the stratigraphic rock according to the two boreholes using formula 1 [1].

$$f = \frac{30 \times f_c + 70 f_m}{100} = 4.7 \quad (1)$$

where f_c and f_m represent the hardness of hard rock and soft rock, respectively. With a rock hardness of f = 4.7, Seam I (12) of the Mong Duong coal mine falls into group 6 in the classification table (Table 739, page 72) for mines that have not been studied for displacement in the “Protection of Structures from the Impact of Underground Mining - 1981 of the former Soviet Union” [1]. Table 1 shows the expected displacement angles for comparison with the displacement angles measured in the field.

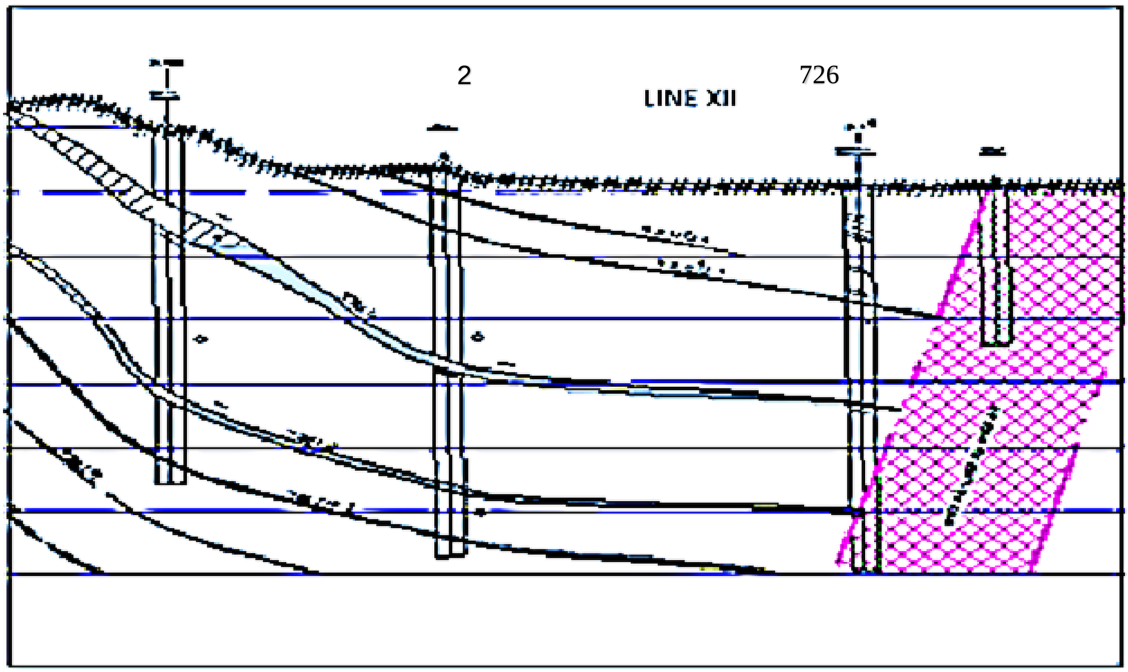


Figure 2. Stratigraphy of borehole 726 and borehole 2.

Table 1. Expected displacement and deformation angles [1].

Boundary Angle			Displacement Angle			Fracture Angle			Displacement Angle in Overburden	Complete Displacement Angle			Maximum Subsidence Angle	Relative Displacement	
d_o	g_o	b_o	d	g	b	d’	g’	b’	j_o	Y1	Y2	Y3	q	q_o	a_o
65	65	39	75	75	50	80	80	46	45	52	56	57	60	0.7	0.3

3. Results and discussions

3.1. Determining displacement parameters on the geomechanical model

To calculate the displacement and deformation for the Mong Duong coal mine in Quang Ninh, it is necessary to study and build a geomechanical model. The author has proposed the elastic modulus $E_C = K_C \times E_R$ (where (E_R) is the elastic modulus calculated from Rockdata, (K_C = 1.24) [5]. Other indices such as cohesion force and internal friction angle are shown in Table 2. The results from running the RS2 model with varying cohesion force and internal friction angle show that the deformation results do not change significantly on the model. Thus, the results for determining the input parameters (E), (C), and (φ) to run the geomechanical model and calculate with the elastic-plastic state for the Mong Duong coal mine in Quang Ninh are recorded in Table 3.

Table 2. Results of determining (E), (C), (φ) for the Mong Duong coal mine according to rockdata.

No	Rock Type	Compressive Strength σ (MPa)	Geological Strength Index (GSI)	Damage Index (D)	Material Constant (mi)	Elastic Modulus E (MPa)	Cohesion Force C (MPa)	Internal Friction Angle φ (degree)
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 3. Results of determining (E_C), (C), (φ) for the Mong Duong coal mine.

No	Coefficient	Sandstone	Siltstone	Shale	Coal
1	E_C	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

Applying the above geomechanical model, the input parameters for the calculation process are the values E, C, φ entered into the Rocscience 2.0 software. The author selected a representative cross-section for specific calculations, which is the cross-section of line XII, and considered its rock layers to be parallel. The stratigraphy of the rock includes sandstone, siltstone, shale, and coal with their respective mechanical parameters. The calculation domain of the model has a width and height of 800×300 m compared to the actual cross-section width of 1500×450 m. However, the area from the monitoring station of Seam I (12) to the outer boundary is 500 m, and the mining level of Seam I (12) ranges from -80 to the surface, which is 250 m, meaning a height of approximately 330 m. Therefore, the author determined that a model size of 800×300 m is reasonable compared to reality and is illustrated in Figure 3.

The longwall mining system is oriented along the strike, with hydraulic supports. The roof control is managed by full caving, with a coal seam thickness of 8 meters and a longwall face length of 80 meters. The parameters for sandstone, siltstone, shale, and coal are entered into the model as shown in Figure 4.

After entering the parameters, the software automatically runs iterative calculations for displacement and deformation, as shown in Figure 5. The calculation results for subsidence are illustrated in Figure 6.

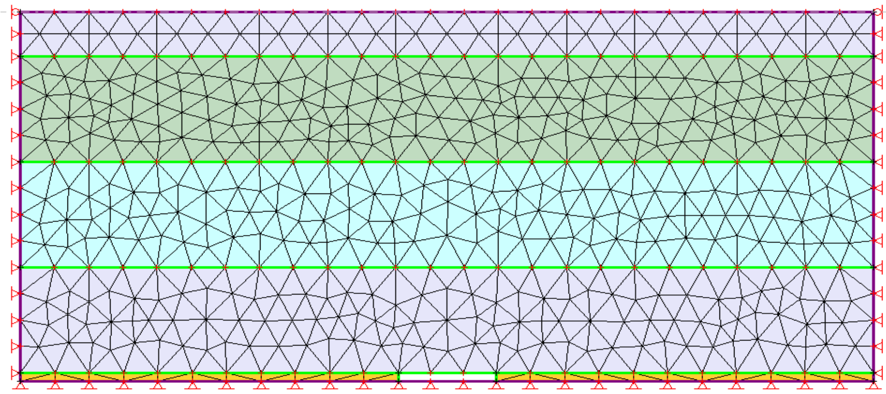


Figure 3. Calculation diagram.

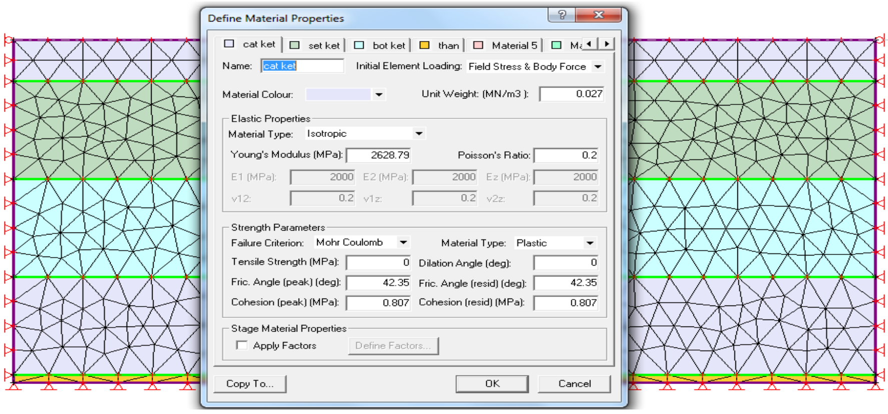


Figure 4. Input parameters for the model.

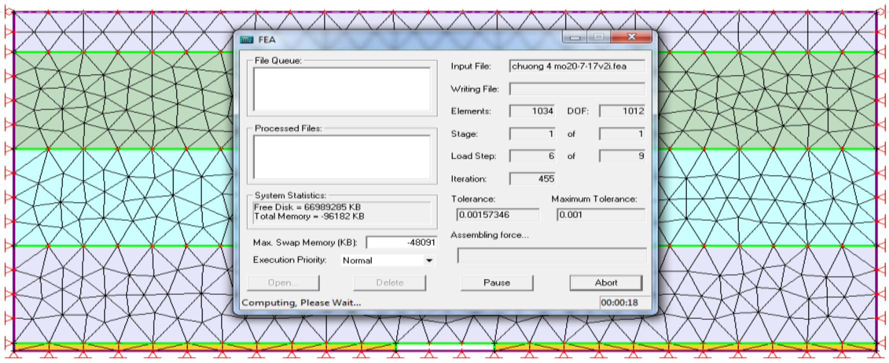


Figure 5. Iterative calculation process for displacement and deformation.

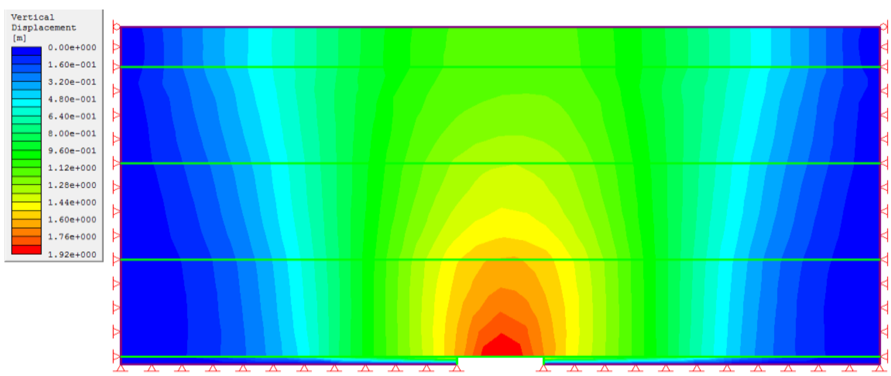


Figure 6. Subsidence chart of rock layers due to underground mining impact.

The determination of subsidence and displacement angles is illustrated in Figure 7.

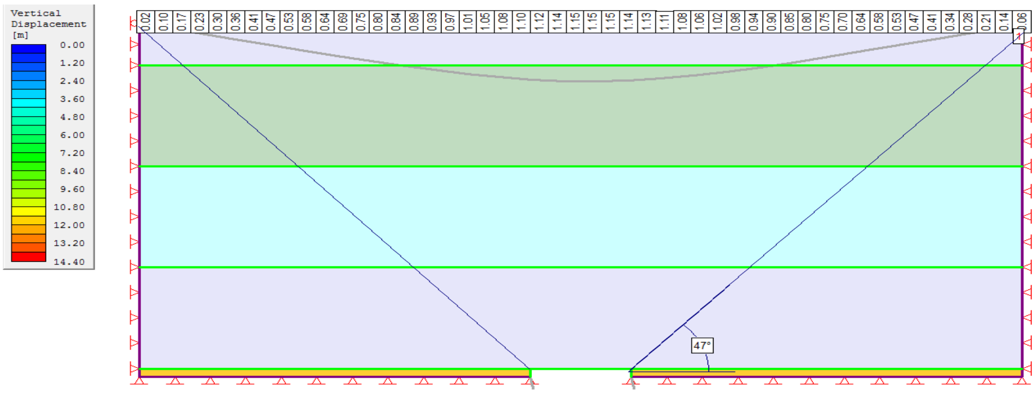


Figure 7. Chart for determining subsidence and displacement angles along the slope.

3.2. Determining displacement parameters through field monitoring

During field measurements, the set 4.120 instrument was used with the following accuracy:

Angle measurement accuracy: (m_t = 5”)

Distance measurement accuracy: ($m_s = (2 + 2\times10^{-6}$ D)) mm (under favorable conditions)

Under unfavorable conditions: ($m_s = (4 + 3\times10^{-6}$ D)) mm

Maximum range: With one prism: 1300 m; With three prisms: 1600 m.

The prism was centered on a fixed base. Based on the processing of monitoring results, permissible and limit deformation indicators were determined. The data processing results after seven field measurements identified the following displacement parameters:

Maximum subsidence: η_{max} = 2244) mm

Maximum tilt: ($i_{max} = 46.8\times10^{-3}$)

Maximum curvature: ($K_{max} = 1.9\times10^{-3}$)

Maximum horizontal deformation: ($\varepsilon_{max} = 61\times10^{-3}$)

Maximum horizontal displacement: (ξ_{max} = 2854) mm

The timeline for the displacement process is as follows:

Start of displacement process: (t = 3 - 4) months

Dangerous displacement period: (t = 5 - 12) months

Gradual displacement period: (t = 13 - 16) months

Signs of displacement cessation: (t = 17 - 21) months

The subsidence and horizontal displacement charts of the monitoring line are shown in Figures 8 and 9.

Currently, the entire monitoring station has not completely ceased, so only a few angle parameters have been determined as follows:

The displacement angle is determined according to the values $\varepsilon = 2\times10^{-3}$, $\eta = 4\times10^{-3}$, k = 0.2×10^{-3}1/m (when the average distance of the sides is from 15 m to 20 m).

The limit displacement angle is determined according to the values $i = 0.5\times10^{-3}$, $\varepsilon = 0.5\times10^{-3}$ (when the average distance of the sides is from 15 m to 20 m).

$\delta = 75^o$ (Strike Displacement Angle)

$\beta = 42^o$ (Downward Slope Displacement Angle)

$\beta_0 = 34^o$ (Limit Downward Slope Displacement Angle)

$\beta' = 52^o$ (Downward Slope Fracture Angle)

$\theta = 57^o$ (Maximum Subsidence Angle)

$\Psi_3 = 52^o$ (Complete Strike Collapse Angle)

In weak surface stratigraphy, such as fault slip surfaces and areas with cracks caused by previous mining activities, the distribution characteristics and values of maximum subsidence have significantly changed [18]. Therefore, the distribution of displacement and deformation on the ground depends on the relative distribution of the roadways' positions compared to areas with weak rock conditions. The total cumulative value of maximum deformation and the distribution of characteristic areas depend not only on mining-geological factors and the seam's position but also on the sequence of roadway development [19–22].

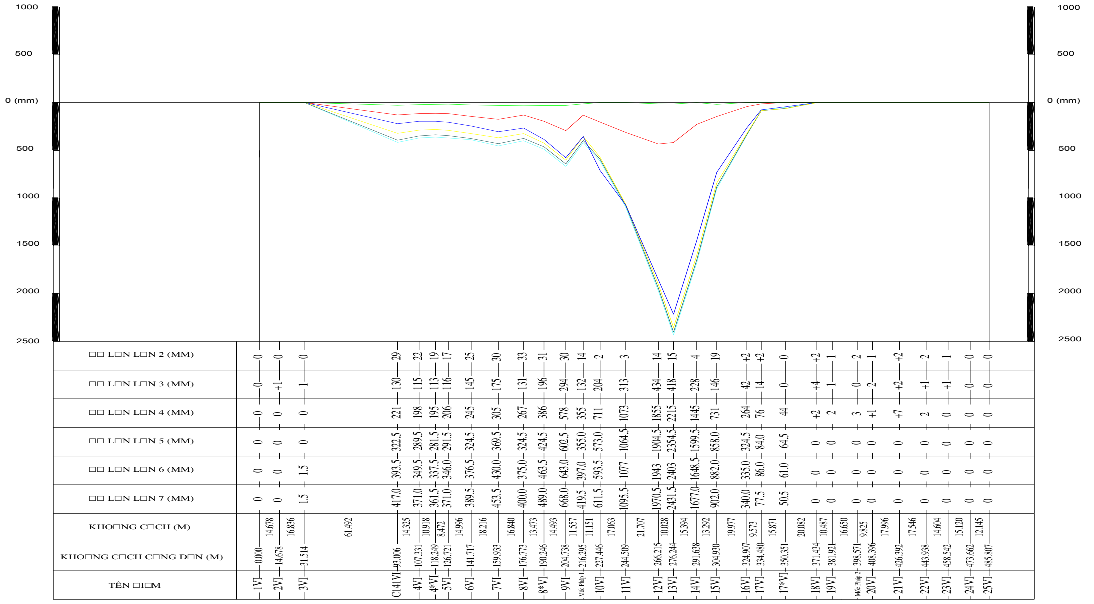


Figure 8. Subsidence chart of line VI.

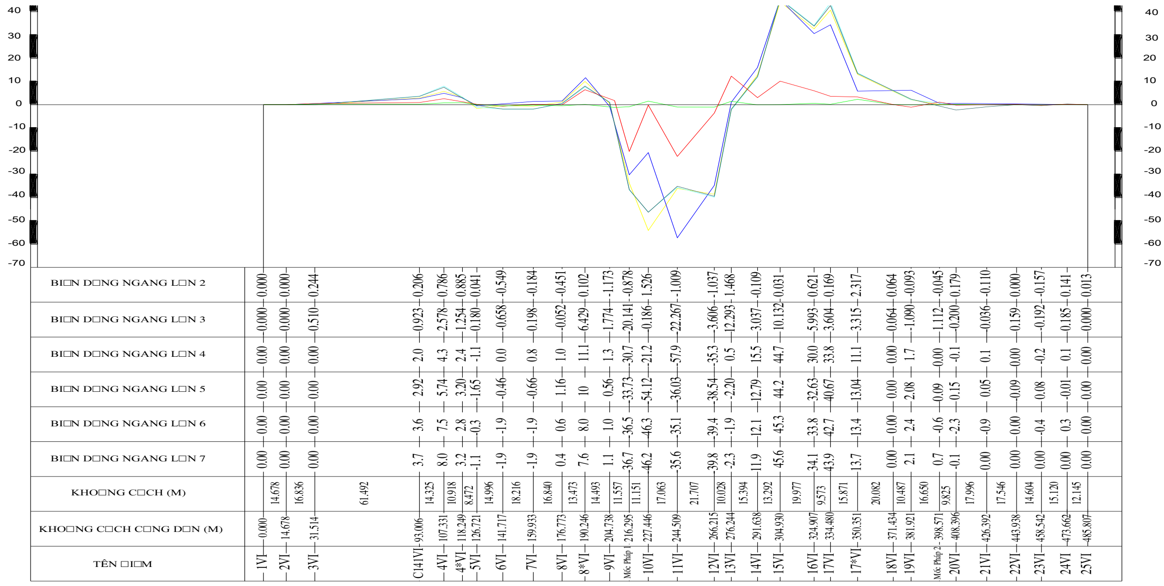


Figure 9. Horizontal deformation chart of line VI.

The initial mining roadways will create areas of poorly bonded stratigraphy, affecting the distribution and value of ground deformation when re-mining. The results of monitoring data processing are shown in Tables 4, 5, and 6 [1, 8, 23]. Boundary Angle, Displacement Angle, Complete Displacement Angle, Maximum Subsidence Angle, Fracture Angle.

Table 4. Comparison of theoretical and experimental results.

Boundary Angle			**Displacement Angle**			**Complete Displacement Angle**		**Maximum Subsidence Angle**		**Fracture Angle**
Expected	measured	difference	Expected	measured	difference	Expected	measured	Expected	measured	measured
β_0=39º (Borehole Stratigraphy)	β_0=34º (mornitoring)	Δ=5º	δ =75º	d = 75º (mornitoring)	Δ=0º	Y_3 = 57º	Y_3 = 52º	q = 60º	q = 57º	b` = 52º
			β=50º	β = 42º (mornitoring)	Δ=8º					

Table 5. Comparison of theoretical and experimental results.

Boundary Angle			**Displacement Angle**			**Complete Displacement Angle**		**Maximum Subsidence Angle**		**Fracture Angle**
Expected	measured	difference	Expected	measured	difference	Expected	measured	Expected	measured	measured
$\beta_0 = 39^o$ (Borehole Stratigraphy)	$\beta_0 = 36^o$ (Geomechanical Model)	$\Delta = 3^o$	$\delta = 75^o$			$Y_3 = 57^o$	$Y_3 = 52^o$	$q = 60^o$	$q = 57^o$	$b' = 52^o$
			$\beta = 50^o$	$\beta = 47^o$ (Geomechanica l Model)	$\Delta = 3^o$					

Table 6. Comparison of theoretical and experimental results.

Boundary Angle			**Displacement Angle**			**Complete Displacement Angle**		**Maximum Subsidence Angle**		**Fracture Angle**
Expected	measured	difference	Expected	measured	difference	Expected	measured	Expected	measured	measured
$\beta_0=36^o$ (Geomechanical Model)	$\beta_0=34^o$ (mornitoring)	$\Delta=2^o$	$\delta=75^o$	$d = 75^o$ (mornitoring)	$\Delta=0^o$	$Y_3 = 57^o$	$Y_3 = 52^o$	$q = 60^o$	$q = 57^o$	$b' = 52^o$
			$\beta = 47^o$ (Geomechanical Model)	$\beta = 42^o$ (mornitoring)	$\Delta=5^o$					

3.3. Discussion

The results of field monitoring and the geomechanical model show that the determined angles deviate from 20 to 50 degrees. The angles from borehole stratigraphy analysis (or the similar region method) deviate from 50 to 80 degrees. This accurately reflects reality, as the similar region method or geomechanical model, when inputting rock parameters, assumes an average and considers the rock stratigraphy to be homogeneous and isotropic. The experimentally measured angles are smaller than those on the numerical model and the expected angles, indicating that the area affected by the mining process is wider, posing a higher safety risk when civil structures are built before mining activities. Therefore, for areas not fully studied for displacement and deformation, the similar region method or geomechanical model can be used to determine displacement angles [7, 8, 24, 25].

4. Conclusion

The research results, borehole stratigraphy analysis, and field measurements form the basis for comparing displacement parameters. These research results allow for determining the relationship between displacement angles under different geological conditions.

Currently, coal mines in Vietnam have not been comprehensively studied for rock and soil displacement and deformation. Therefore, when setting up monitoring stations, it is necessary to evaluate and analyze the stratigraphy of boreholes passing through the area to obtain the rock hardness coefficient (f) to determine the expected displacement angle or input data into the numerical geomechanical model. Based on this, the area to be studied should be increased by one level in the mine classification standard to ensure a wider deformation area, ensuring safety for surface structures. Due to the lack of comprehensive studies, the results are only applicable on a narrow scale, and more research projects are needed at various mines to obtain displacement parameters for standardization.

Based on the basic processing of monitoring data, the displacement angles were determined as ($\beta = 42^o$) from field monitoring ($\beta = 47^o$) from the geomechanical model, and ($\beta = 50^o$) from borehole stratigraphy analysis (similar region method). The angles measured from the monitoring station are smaller than the expected angles and those on the numerical model, accurately reflecting reality.

Author contribution statement: Writing and original draft preparation: P.V.C.; Review and editing: P.V.C.; Calculation and visualization: P.V.C.; Project administration: P.V.C.; All authors have read and agreed to the published version of the manuscript.

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

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