

Article

Deformation Laws of Coal Mining-Affected Slopes in Loess Gully Area

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Abstract

The loess gully region is characterized by complex terrain with crisscrossing gullies, where coal mining can readily induce surface subsidence and slope deformation. Such deformation often leads to geological hazards and ecological issues, including collapses, landslides, soil erosion, vegetation dry up, and land degradation. Therefore, understanding the deformation behavior of mining-induced slopes is essential for the restoration and management of mine geological environments. This study focuses on five slopes within working faces 50205 and 50206 of the Zhen'er Coal Mine in Fugu County. Using a combination of 3DEC numerical simulations and orthophoto-based fracture identification, we systematically investigated mining-induced slope deformation under the complex topographic conditions of the loess gully region. The goal is to answer three key questions: where mining-induced slope deformation primarily occurs, how it evolves over time, and what the main controlling factors are. Spatially, the primary deformation zones and their propagation paths vary significantly among the five slopes. The largest deformation occurs in the slope body directly above the main section of the working face, gradually decreasing toward the edges of the working face. Temporally, mining-induced slope deformation exhibits a time lag, meaning that surface responses lag behind underground mining activities and continue to develop even after the working face is fully extracted. In the loess gully region, slope deformation induced by mining is controlled not only by mining activities but also by topographic factors such as slope shape, aspect, gradient, and height. The spatiotemporal evolution of deformation becomes even more complex for slopes that span multiple working faces. These findings provide a scientific basis for monitoring mining-induced slope deformation and preventing geological disasters in the loess gully region, while also offering practical guidance for safe mining operations and hazard control in similar settings.



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Keywords: mining-affected slopes; loess gully region; deformation; spatiotemporal evolution law; Zhen'er coal mine

1. Introduction

There are substantial coal resources buried in western China, of which more than 60% of mines are located in loess gully areas, which are mainly distributed in Shaanxi, Shanxi, Gansu, Ningxia, Inner Mongolia, etc. Gully areas, a transition between plain and plateau, are characterized by narrow and steep channels and complex engineering geological conditions [1,2]. A series of mining damages and geological disasters as well as ecological

problems appear in different forms, such as surface cracks, step subsidence, slope slide, local collapse, vegetation dry-up, land desertification, etc. [3]. The slope deformation induced by coal mining not only occurs during the extraction period but also may experience residual subsidence or reverse movement after mining ceases or even after the mine is closed. At the same time, the mining of a shallow-buried coal seam would easily cause sliding fissures due to the combined effect of the geological mining environment and gully topography in loess gully areas [4,5]. Because of the mining-induced loess slopes' gentle tensile strength, loess slopes subside severely when their stable internal structure is damaged, caused by underground coal mining [1]. Therefore, over the past 20 years, in connection with the specific mining engineering practice, some experts, scholars and engineers have done a certain amount of research work on loess slope deformation and failure under underground mining; slope deformation and failure laws were studied mostly by numerical simulation and by model experiment, field monitoring and a combined method partly [6–8]. Therein, Zhang [9] presents details of highway slopes affected by a mining subsidence event that occurred in the Yangquan coal mining area of China in 2016. Prof. Sun Shiguo did great and groundbreaking work. He explored the influence law of slope stability induced by underground mining areas and the relative position and space and geometry size changes of slope body [10]. He also studied the influence of underground mining on the outer region on slope stability characteristics [11].

Wen [12] took the Hongyu Coal Mine as the engineering background; the volume and slope of the gully landform above the goaf were included in the influence factors of dynamic pressure characteristics, and the analysis framework of topography and geomorphology was constructed. Liu [4] used FLAC^{3D} numerical simulation software to establish the model of a concave slope, convex slope, mixed slope and uniform slope to simulate the influence of underground coal mining on surface morphology. Zhang [7] studied gully slope movements, subject to underground mining, with physical simulation and theoretical analysis. The rules disclose that the slope rock slides horizontally in response to mining in the direction of gullies and rotates reversely with the appearance of a polygon block in mining away from gullies. Li [8] proposes an intelligent slope stability prediction method based on the improved pelican optimization algorithm (IPOA) and the optimization random forest (RF) algorithm to reduce disasters and accidents caused by slope instability. A set of intelligent slope stability prediction systems is created using MATLAB tools and applied to Lala Copper Mine in Sichuan Province. Xu Dongjing [13] proposed a conceptual model, which includes the broken patterns of the overburden strata and the fracture space induced by it. The authors proposed three types of trapezoidal broken models considering the top-down varying pattern of the lateral and longitudinal volume expansion coefficients. Lv [14] analyzed the effects of the fault in controlling the deformation features of the destabilized slope during underground mining by adopting the method of numerical simulation from these perspectives, including displacement, stress, and strain, among others.

Previous research has made great progress in areas such as the overall response of coal seam mining, the evolution of mining-induced slope deformation, and the integration of monitoring and simulation. However, systematic research on mining-affected slope deformation under complex terrain conditions in loess gully regions remains relatively scarce; in particular, there is still a lack of in-depth understanding regarding the differential responses of different slopes, the spatiotemporal evolution patterns, and their corresponding relationships with ground surface deformation. As is well known, the deformation of mining-affected slopes in loess gully regions is jointly controlled by multiple factors such as topographic conditions, mining methods, and overburden structure, leading to complex patterns. Therefore, it is necessary to integrate topographic conditions and comprehen-

sively apply field investigation and numerical simulation methods to conduct systematic research on the deformation laws of mining-affected slopes in loess gully regions.

The purpose of this paper is to study deformation laws on different types of slopes located on the coal working face in the loess gully regions in order to better answer questions such as how they change over time, where they change in space, and what factors drive their change. This will enable a more comprehensive revelation of the spatiotemporal evolution mechanisms of mining-induced slope deformation, which is crucial for the prevention and control of geological disasters in the loess gully regions.

2. Coal Mine Summary

The Zhen'er Coal Mine is located in FuGu County, ShaanXi Province, China (Figure 1a). The mining area features crisscrossing gullies, with relatively gentle ridge tops sloping toward the valleys at gradients of 10° to 20° . The gullies are generally 80 to 100 m deep. Below the gully edge lines, the valley slopes are steeper, ranging from about 60° to 80° . The gully bottoms are relatively flat, flanked by steep sides that locally form cliffs. This area is characterized by typical loess hilly-gully topography. The surface of the mining area is largely covered by Quaternary sediments. The strata, from oldest to youngest, are as follows: the Lower Jurassic Fuxian Formation (J_1f), the Middle Jurassic Yan'an Formation (J_2y), the Pliocene Jingle Formation (N_2j), the Middle Pleistocene Lishi Formation (Q_2l), and the Holocene alluvial-proluvial deposits (Q_4^{2al+pl}).

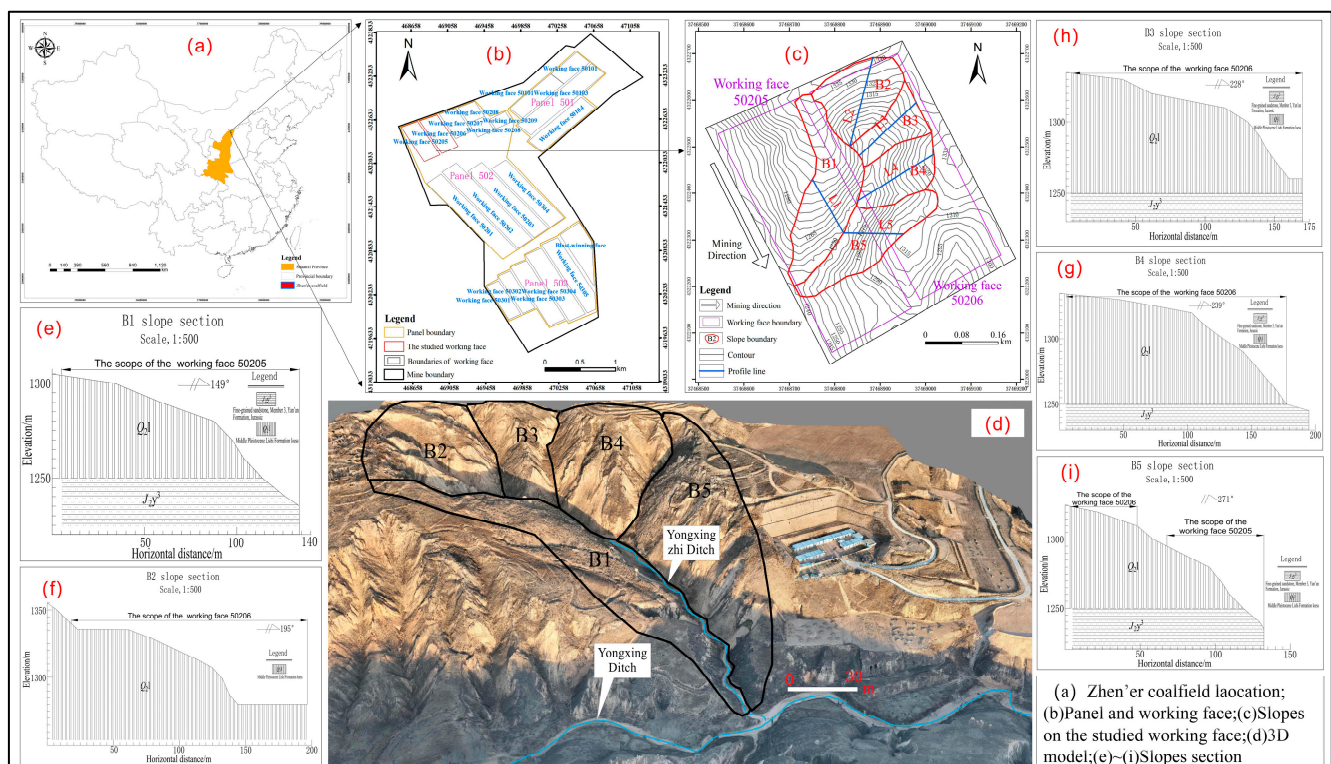


Figure 1. Location of research area and research slope section (B1~B5).

The Zhen'er Coal Mine is located in the southeastern part of the Northern Shaanxi Slope, a secondary tectonic unit of the Ordos Basin. The geological structure is simple, with no evidence of magmatic activity in the area. The overall structural form is a gently north-dipping monocline, with a dip direction of 5° and a dip angle of less than 1° . Locally, very small-scale nose-shaped uplifts are developed. The regional crust is stable, and historically no major destructive earthquakes have ever occurred in the area. The characteristic period

of the ground motion response spectrum in this region is 0.35 s, the peak ground acceleration is 0.05 g, and the seismic fortification intensity is VI.

The Zhen'er Coal Mine was mined from 2008 to December 2021 and is now closed. The main minable coal seam within its mining rights is the No. 5⁻² coal seam, with thickness varying from 1.45 m to 3.58 m (average 2.82 m), burial depth ranging from 74.37 m to 176.86 m (typically 90~130 m), and floor elevation varying between 1138.25 m and 1164.90 m. The coal seam dips northward with a dip direction of 5° and an average dip angle of 0.5°. The mining of the No. 5⁻² coal seam is divided into three panels: 501, 502, and 503. Panel 501 is located in the northern part of the mining area, Panel 502 in the central part, and Panel 503 in the southern part (Figure 1b). The working faces 50205 and 50206 studied in this research are located within Panel 502 (Figure 1b), mined from January to June 2017 (50205) and July to December 2019 (50206). The mining height of the coal seam is 3 m, with an average burial depth of 138 m. The advancing direction azimuth is 151°. Each working face has a length of 540 m and a width of 200 m. The mining method is longwall retreating with full-seam one-pass mining, using fully mechanized mining technology and a full caving method for roof management. Based on high-resolution orthophoto images of the study area, through manual identification, taking the main gullies (ignoring smaller secondary gullies) as the main line, combined with ridge lines and slope morphology characteristics, the boundaries of slopes within working faces 50205 and 50206 were delineated. A total of five slopes (B1 to B5) were identified (Figure 1c,d), with unit areas ranging from 0.125 to 0.352 km². The material composition of B2 and B3 slopes is loess (Q₂l). The material composition of B1, B4, B5 slopes is loess (Q₂l) and fine-grained sandstone (J₂y³). The main characteristics of each slope are shown in Table 1 and Figure 1e–i.

Table 1. Main characteristics of slopes B1~B5.

Slope ID	Slope Type	Slope Aspect /°	Angle Between Slope Aspect and Mining Direction /°	Slope Gradient /°	Slope Height /m	Whether Crossing Working Face
B1	convex	117	33	60	100	YES
B2	Concave	181	31	45	48	NO
B3	convex	230	80	16.5	54	NO
B4	convex	252	100	22.3	72	NO
B5	Straight	320	170	31	75	YES

3. Methods

3.1. Model

Using the measured terrain of working faces 50205 and 50206 as the prototype, a three-dimensional numerical model capable of realistically representing the complex topographic structure was constructed using the 3DEC discrete element software (version 7.0, Itasca Consulting Group, Inc., Minneapolis, MN, USA). In the spatial coordinate system, the X-axis is defined as the working face advancement direction, the Y-axis as the working face dip direction, and the Z-axis as the vertical height direction. The horizontally layered model dimensions are 580 m × 460 m × 100 m. The loess layer model varies in height with the surface topography, but its width and length are consistent with those of the underlying horizontally layered model. To eliminate boundary effects, a 20 m protective coal pillar is left on all four sides of the model. Based on geological data, a grid model consisting of 16 layers and 9 types of rock/soil masses was established, comprising 42,688 discrete blocks, 42,3295 computational nodes, and 384,168 computational grids, as shown in Figure 2. The

block zone cmodel is assigned Mohr–Coulomb elasto-plastic, and the block contact jmodel is assigned Mohr. The yield criterion is the Mohr–Coulomb criterion, and the flow rule is non-associated with a constant dilation angle of 5°.

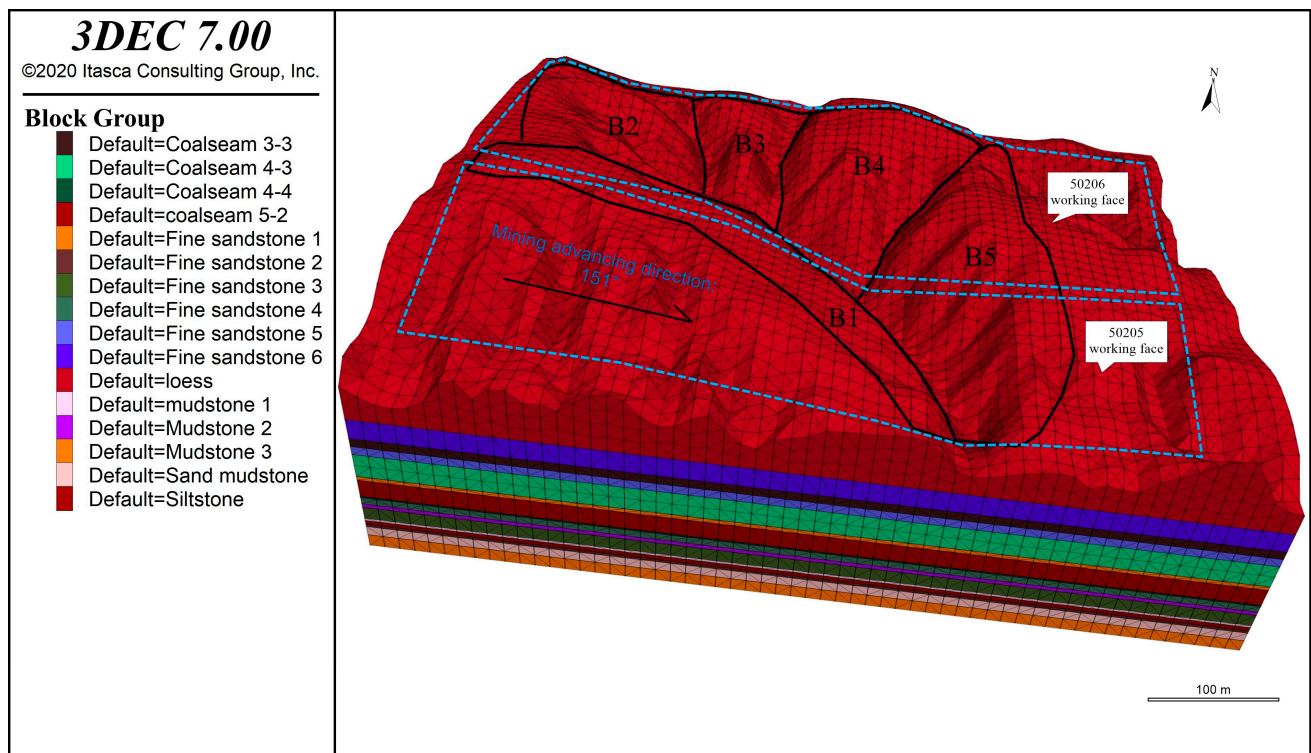


Figure 2. A 3D discrete element model of mining-induced overburden and loess strata at working faces 50205 and 50206, Zhen'er Coal Mine.

3.2. Parameter Assignment

3.2.1. Stratigraphic Material Parameters

The mechanical properties of the loess layer were obtained through laboratory tests; the mechanical parameters of the rock were mainly based on previous test results from the mining area. The specific parameter assignments are shown in Table 2.

Table 2. Physical and Mechanical Parameters of Rock/Soil Masses.

Strata	Density $\rho/\text{kg}\cdot\text{m}^{-3}$	Bulk Modulus K/MPa	Shear Modulus G/MPa	Cohesion C/kPa	Friction Angle $\phi/^\circ$
Loess	1370	30	18	143.67	8.34
Siltstone	2210	1298.3	741.9	279.5	26.4
Fine sandstone	2360	1591.7	955.0	877.5	25.6
Sandy mudstone	2490	2498.5	1645.4	526.5	25.4
3 ⁻³ coal seam	1400	5400.5	610	1810	24.8
4 ⁻³ coal seam	1400	5400.5	610	1810	24.8
4 ⁻⁴ coal seam	1400	5400.5	610	1810	24.8
5 ⁻² coal seam	1400	5400.5	610	1810	24.8
mudstone	2540	1914.9	1148.9	383.5	24.1

Note: The assignments for the 6 layers of fine sandstone are the same, and the assignments for the 3 layers of mudstone are also the same.

3.2.2. Setting of Stratigraphic Contact Surface Parameters

To ensure computational stability, the contact surface parameters are assigned following the stiffness matching principle in the 3DEC official manual. The cohesion c is reduced

by 15% to 30%, and the tensile strength is set to one-quarter of the cohesion. The internal friction angle is calculated based on the normal stiffness and shear stiffness, using the bulk modulus K and shear modulus G of the stratigraphic parameters. The model contact surface parameters are shown in Table 3.

Table 3. Summary of mechanical parameters for model contact surfaces.

Interface Position	Bedding Plane Height	Mesh Size	Normal Stiffness /GPa·m ⁻¹	Shear Stiffness /GPa·m ⁻¹	Cohesion /kPa	Friction Angle /°	Tensile Strength /kPa
Fine sandstone/sandy mudstone	9	7	0.41	0.21	200	22	50
Sandy mudstone/fine sandstone	16	2	1.43	0.72	200	22	50
Fine sandstone/5 ⁻² coal seam	18	2	0.65	0.33	100	18	25
5 ⁻² coal seam/mudstone	21	2	1.25	0.63	100	18	25
mudstone/Fine sandstone	23	2	1.43	0.72	200	22	50
Fine sandstone/mudstone	32	3	0.95	0.48	200	22	50
mudstone/Fine sandstone	35	3	0.95	0.48	200	22	50
Fine sandstone/4 ⁻⁴ coal seam	40	1	1.31	0.66	100	18	25
4 ⁻⁴ coal seam/Siltstone	41	1	1.31	0.66	100	18	25
Siltstone/mudstone	54	3	0.95	0.48	200	22	50
mudstone/4 ⁻³ coal seam	57	3	1.43	0.22	100	18	25
4 ⁻³ coal seam/Fine sandstone	74	6	1.21	0.11	100	18	25
Fine sandstone/3 ⁻³ coal seam	80	6	1.22	0.11	80	16	20
3 ⁻³ coal seam/Fine sandstone	86	6	0.48	0.24	100	18	25
Fine sandstone/loess	100	14	0.20	0.10	20	12	0

3.3. Boundary Condition Setting and Calculation Scheme Design

3.3.1. Boundary Conditions

Spatial constraints are implemented by limiting the velocities of boundary grid points. The fine sandstone at the model bottom is restricted from displacement in the X, Y, and Z directions. The lateral sides around the model are restricted from horizontal displacement in either the X or Y direction, allowing vertical free deformation while simulating the lateral confinement effect of an infinite rock mass.

3.3.2. Initial Equilibrium

The initial equilibrium calculation aims to eliminate the influence of initial stratigraphic deformation on subsequent mining analysis and is a prerequisite for simulating coal seam mining. An equivalent self-weight load is applied according to the natural burial depth conditions of the strata, and local damping is used to accelerate energy dissipation in the model, shortening the convergence time. During the solution process, the maximum unbalanced force ratio threshold is set to 1×10^{-5} . When the iteration falls below this threshold, the initial equilibrium of the model is considered complete. To remove the initial deformation caused by self-weight and ensure that subsequent deformation is solely induced by excavation activities, the displacements and velocities of all grid points are initialized to zero via a command. Based on this initial state, the excavation and caved-zone modeling procedures are subsequently applied.

3.3.3. Calculation Scheme

The simulated excavation range is set from $X = 20$ m to $X = 560$ m, with a total advancement length of 540 m. The step distance during the mining advancement process is set to 10 m. At each excavation step, the program automatically deletes the blocks in

the corresponding area of the 5⁻² coal seam by executing the block excavate command. To account for the formation of the caving zone and the supporting effect of caved rocks, the resulting void is immediately filled with a caved rock material that obeys a double-yield constitutive model, which captures the processes of bulking, compaction, and the gradual increase of residual bearing capacity. The bulking factor, compaction modulus, and friction angle are calibrated against empirical data for caved zones in longwall panels. The interaction between the caved rocks and the roof is simulated through automatic contact and load transfer; as the roof converges, the caved material compacts and provides increasing support. After each excavation-filling step, the model performs preliminary iterations with a step limit of 2000 and a convergence threshold of 1×10^{-5} to simulate the coal seam mining process. After the working face extraction is completed, a secondary equilibrium calculation is carried out with the threshold reset to 1×10^{-5} to simulate the residual deformation of the overburden after mining.

4. Results

4.1. Spatial Characteristics of Mining-Induced Slope Deformation

4.1.1. Slope Surface Deformation

Because the deformation of the mining-affected slope is predominantly vertical (subsidence), we used the block displacement in the Z-direction to analyze the slope deformation. The block Z displacement cloud maps of the slope surfaces for B1 to B5 are shown in Figure 3.

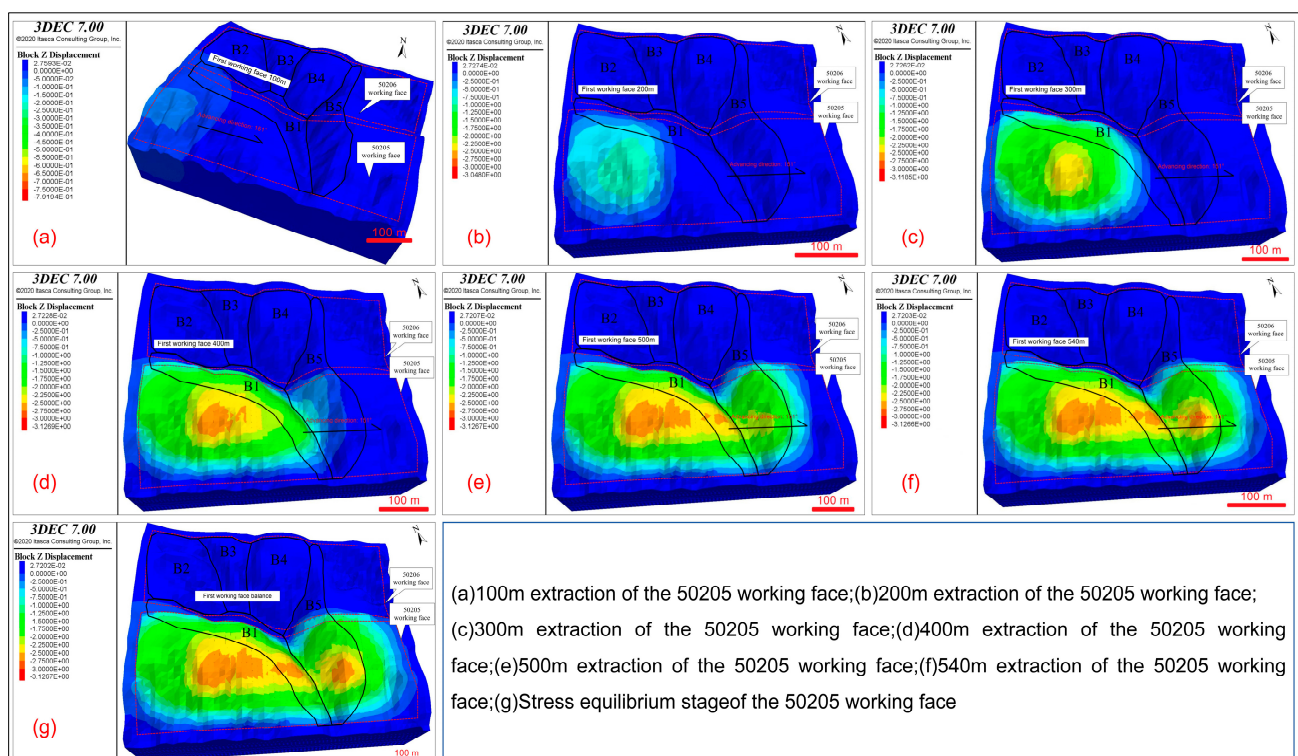


Figure 3. Cloud map of slope surface displacement during working face 50205 mining.

When the 50205 working face was excavated to 100~200 m (Figure 3a,b), the slope surface deformation range of the B1 slope was small, occurring only at the slope crest, with a maximum value of about 0.75 m. As mining progressed, the deformation zone gradually expanded and extended toward the middle of the B1 slope, where a relatively significant deformation zone first appeared. Meanwhile, deformation gradually spread to the slope toe (Figure 3c,d), but the region with larger deformation remained at the slope crest, with a maximum value

of about 2.75 m. After mining reached 500 m (Figure 3e–g), a large deformation occurred in the southwestern part of the B1 slope near the slope toe, reaching a maximum value of 3.128 m. During the mining of the 50205 working face, the northern gully area of the B1 slope experienced almost no deformation (less than 0.25 m). When the adjacent 50206 working face was excavated to 200 m (Figure 4a,b), deformation began to appear, reaching 0.50 m. By the time it reached 300 m (Figure 4c), the slope displacement directly above the coal pillar between the two working faces had expanded to about 1 m, and thereafter until the completion of mining, it remained basically around 1 m (Figure 4d–g).

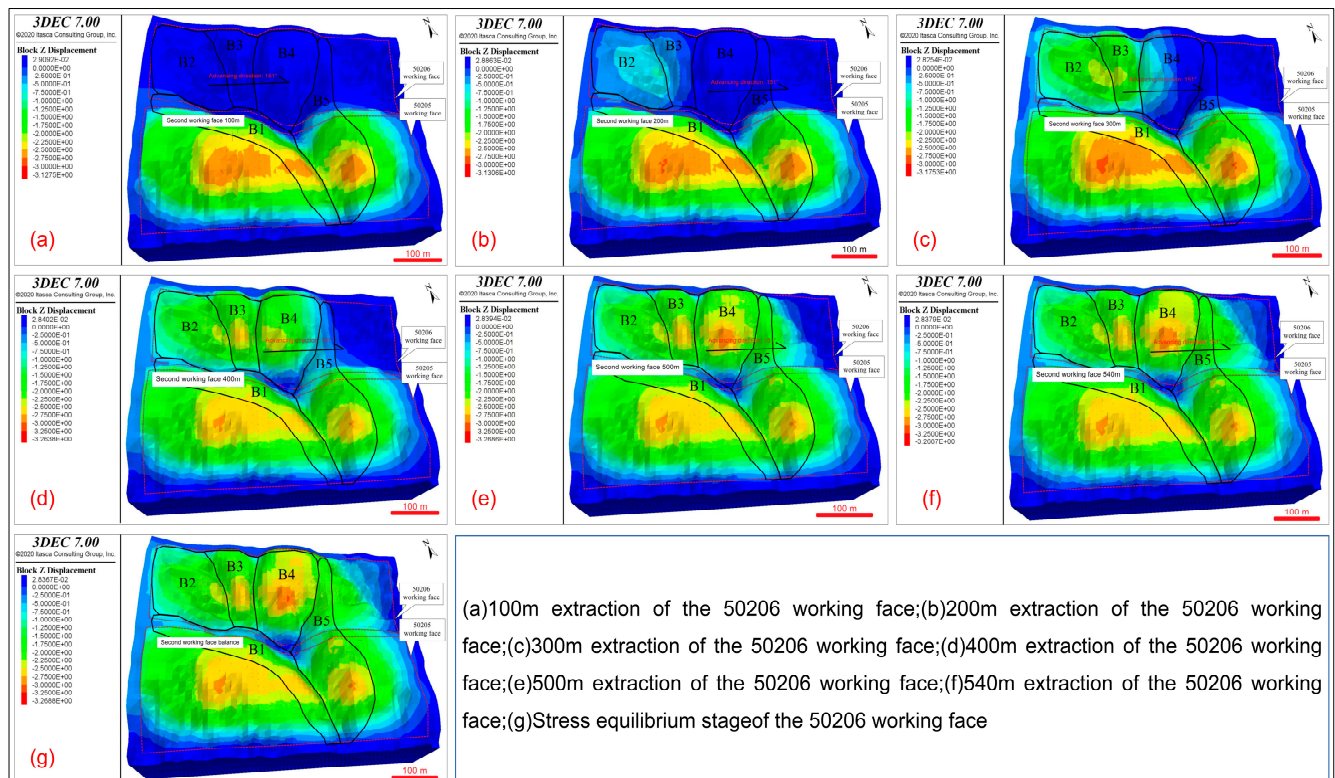


Figure 4. Cloud map of slope surface displacement during working face 50206 mining.

During the mining of the 50205 working face, the B2 slope experienced almost no deformation. However, because it is located above the open-off cut of the 50206 working face, significant deformation occurred at the early stage of mining of the 50206 working face. The displacement at the northwest corner was between 0.50 m and 0.75 m (Figure 4a).

When mining advanced to 200 m, obvious deformation appeared on the slope surface in the central area, with displacements between 0.50 m and 1.00 m (Figure 4b). As mining progressed to 300–400 m, the subsidence range further expanded, deformation gradually spread from the central area to the entire slope surface and continued to develop toward the slope toe. The slope surface displacements ranged from 0.75 m to 2.48 m (Figure 4c,d). When mining reached 500–540 m, the overall deformation pattern of the slope was basically formed. In the later stage, deformation continued to increase slowly mainly along the original high-value areas, with slope surface displacements ranging from 0.75 m to 2.7 m (Figure 4e–g).

Slope B3 is nearly perpendicular to the mining direction of the 50206 working face, with its center located 230 m from the open-off cut along the advancing direction. When mining advanced to 100 m, no obvious displacement was observed on the slope surface (Figure 4a). When mining advanced to 200 m, noticeable deformation first appeared at the gully at the slope toe, with a maximum displacement of 0.75 m. The overall deformation

pattern showed a gradually decreasing trend from the toe on both the north and south sides toward the central ridge of the slope (Figure 4b). As mining advanced to 300~400 m, deformation had covered the entire slope. High-deformation zones gradually formed at the central ridge and the northern gully, with more significant deformation at the western ridge, reaching a maximum of 3.00 m (Figure 4c,d). When mining advanced to 500~540 m, the deformation at the western ridge reached a maximum of 3.27 m. The deformation at the north and south gullies was relatively smaller but still reached 1.50 m (Figure 4e-g).

The center of Slope B4 is located 350 m from the open-off cut of the 50206 working face along the advancing direction. During the mining stage of 100~200 m, no obvious deformation was observed on the slope surface (Figure 4a,b). When mining advanced to 300 m, deformation began to appear in the northern part of the slope surface, with a maximum displacement of 1.5 m (Figure 4c). When mining advanced to 400 m, a high-deformation zone developed in the northern area, most prominently at protruding parts and gully incision areas, where the maximum displacement reached 3.0 m (Figure 4d). In the later mining stage (500~540 m), deformation occurred over the entire slope surface, with displacements ranging from 0.5 m to 3.27 m. The high-deformation zone gradually shifted toward the central part and was mainly concentrated in areas with significant topographic relief on the slope surface (Figure 4e-g).

Slope B5 spans across the two working faces, 50205 and 50206. When the 50205 working face was mined to 100~300 m, no obvious deformation was observed on the slope surface (Figure 3a-c). After the 50205 working face advanced beyond 400 m, noticeable displacement began to appear in the western part of the slope. The high-deformation zone was located at the topographic transition where the slope changed from gentle to steep, with a maximum displacement of 3.13 m (Figure 3d-g). During the early mining stage of the 50206 working face (100~300 m), because it was relatively far from the open-off cut, no obvious deformation occurred in the eastern part of the B5 slope either. The western part of the slope above the 50205 working face was in a residual deformation stage, with a slight increase in the maximum value to 3.18 m (Figure 4a-c). In the middle and late mining stages (400~540 m), significant deformation also appeared in the eastern part, with displacement values ranging from 0 to 2.25 m. The area with small deformation was located on the coal pillar between the two working faces. The maximum deformation in the eastern part occurred in the southern area, which is close to the subsidence center of the 50206 working face. The maximum displacement in the western deformation zone continued to increase, reaching 3.27 m (Figure 4d-g).

4.1.2. Slope Internal Deformation

To facilitate the analysis of internal deformation within the slopes, one section line is arranged on each slope, named L1 to L5, respectively. The direction of the sections is approximately perpendicular to the contour lines, as shown in Figure 5.

A block displacement cloud map slice was created along line L1, as shown in Figure 6. When mining advanced to 100 m, the overall internal deformation of the B1 slope was relatively weak, with only a small-scale displacement response occurring above the open-off cut. The maximum displacement was 0.15 m, mainly characterized by slow subsidence (Figure 6a). When mining advanced to 200~400 m, the internal displacement of the slope gradually concentrated toward the central part, forming a distinct high-displacement zone. This high-displacement zone migrated toward the upper part of the slope and gradually extended to the slope surface, with the maximum displacement increasing from 1.35 m to 3.01 m (Figure 6b-d). After mining reached 500 m, although the maximum displacement did not change significantly compared with that at 400 m, deformation in the lower part of the slope and near the slope toe increased notably (Figure 6e,f).

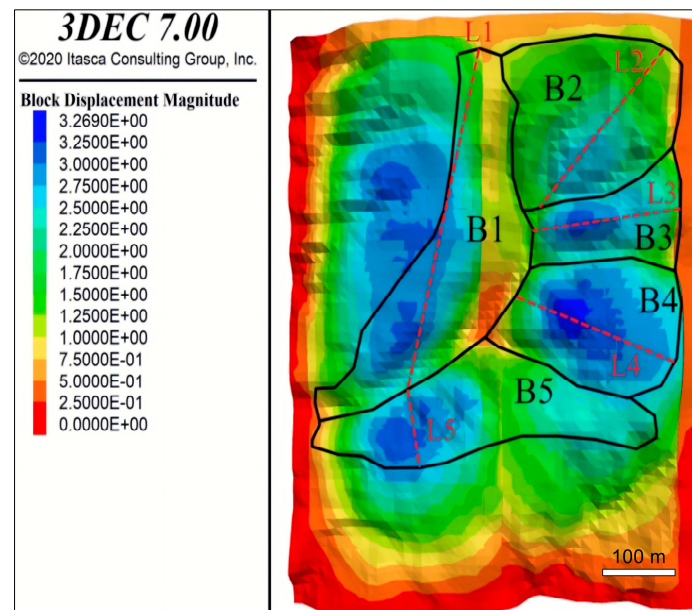


Figure 5. Slope unit division and secant line layout plan.

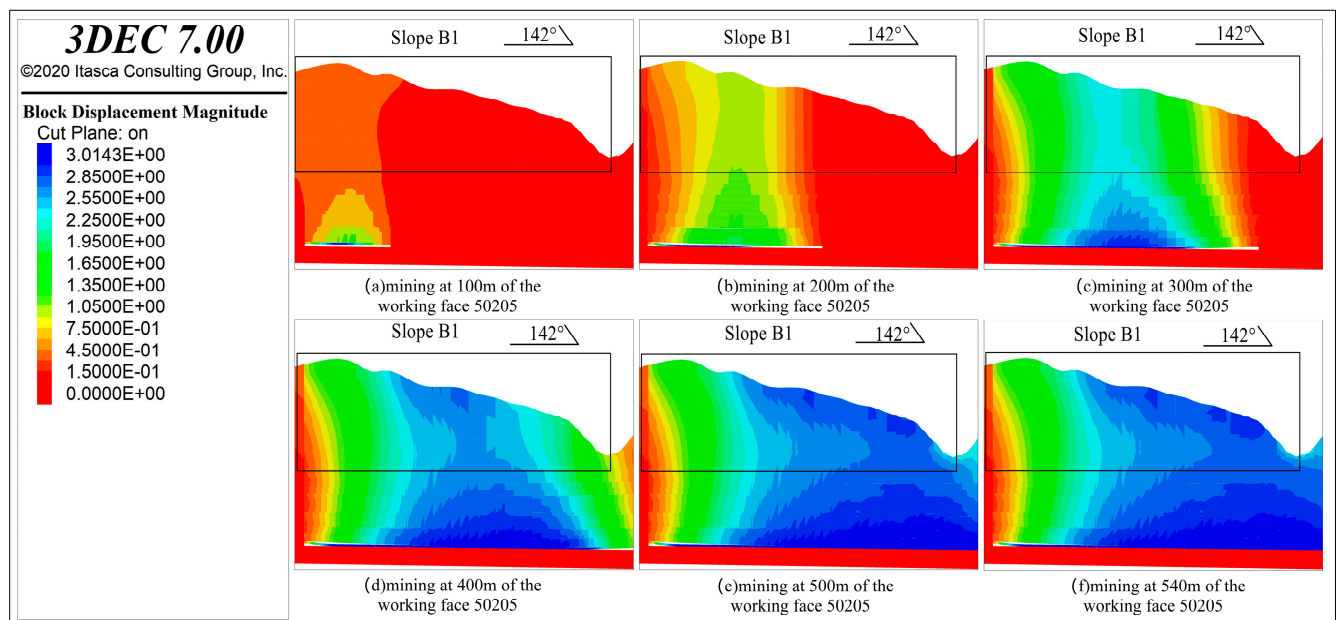


Figure 6. Deformation profile of Slope B1.

A block displacement cloud map slice was created along line L2, as shown in Figure 7. At 100 m of mining, the overburden displacement had not yet propagated to the B2 slope area, and no obvious deformation was observed inside the slope overall (Figure 7a). After mining reached 200 m, the roof began to collapse, and the overburden displacement rapidly transferred to the central part of the slope, forming a relatively distinct deformation zone there, while deformation at the slope toe and crest remained relatively small. The maximum internal displacement in the slope reached 1.05 m (Figure 7b). By the time mining advanced to 300 m, obvious displacement appeared throughout the slope interior, with displacement values ranging from 1.05 m to 2.55 m (Figure 7c). As mining advanced from 400 m to 540 m, because the mining face had passed the B2 slope, the internal deformation of the slope showed no significant change, except that the extent of the high-value zone (2.25~2.55 m) increased slightly (Figure 7d–f).

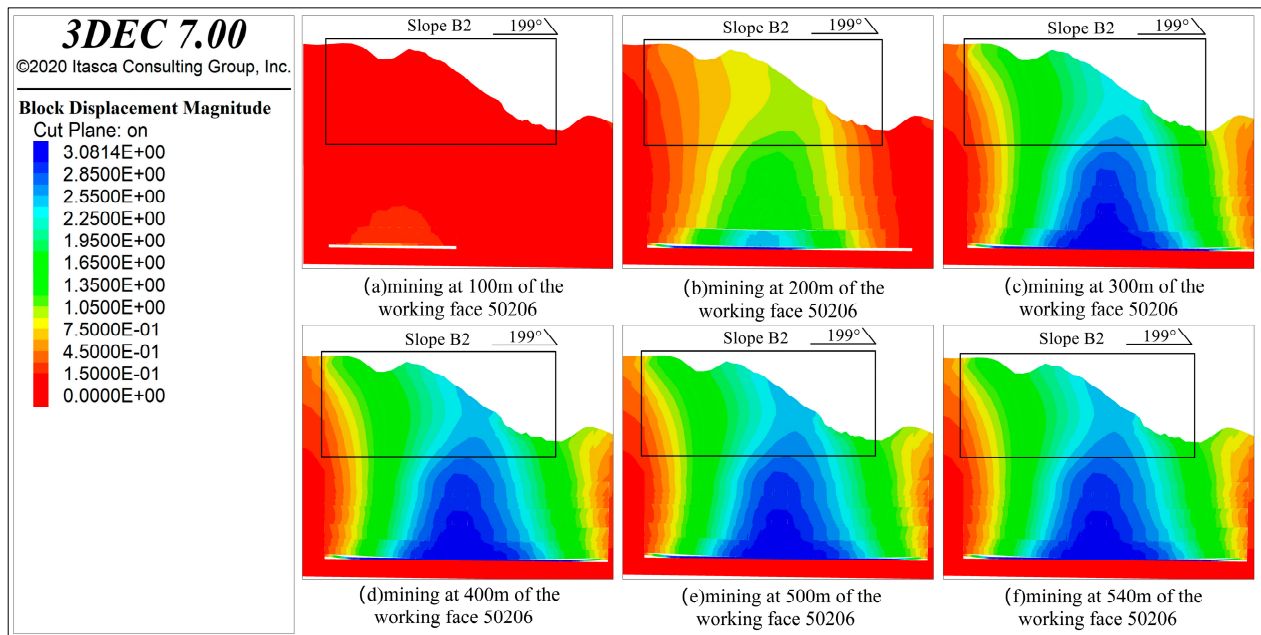


Figure 7. Deformation profile of Slope B2.

A block displacement cloud map slice was created along line L3, as shown in Figure 8. At 100 m of mining, the working face had not yet advanced beneath the slope, and no obvious deformation was observed inside the B3 slope (Figure 8a). When mining advanced to 200 m, the working face had already progressed to the lower part of the slope, but the overlying strata had not yet collapsed significantly; only a weak displacement response was exhibited inside the slope, with the central part being most affected, followed by the upper and lower parts. The overall deformation was still relatively small, with a maximum value of 0.75 m (Figure 8b). When mining advanced to 300–400 m, the overlying strata began to collapse, and the subsidence displacement of the goaf rapidly transferred into the slope interior. A distinct high-displacement zone first formed in the central part of the slope, reaching a maximum value of 2.85 m, and gradually migrated toward the slope surface (Figure 8c,d). When mining advanced to 500–540 m, the internal deformation of the slope mainly manifested as a continuous increase in the original high-displacement zone (maximum reaching 3.09 m) and a slow expansion of the affected area, with the overall change tending to stabilize (Figure 8e,f).

A block displacement cloud map slice was created along line L4, as shown in Figure 9. When mining advanced to 100–200 m, the working face had not yet advanced beneath the B4 slope, and no obvious displacement response was observed inside the slope (Figure 9a,b). When mining advanced to 300 m, a relatively clear internal displacement zone appeared in the middle-lower part of the slope. Its distribution pattern was consistent with the subsidence basin above the working face, generally showing larger displacement in the middle-lower part, with a maximum value of 1.00 m (Figure 9c). When mining advanced to 400–540 m, the displacement in the middle part of the slope continued to increase, with the maximum value changing from 2.75 m to 3.17 m and gradually extending toward the slope toe. The internal deformation range rapidly expanded toward the upper part of the slope. Although the slope gradient in the lower part was relatively steep, no significant increase in displacement was observed there, and the overall deformation remained mainly at low values (Figure 9d–f).

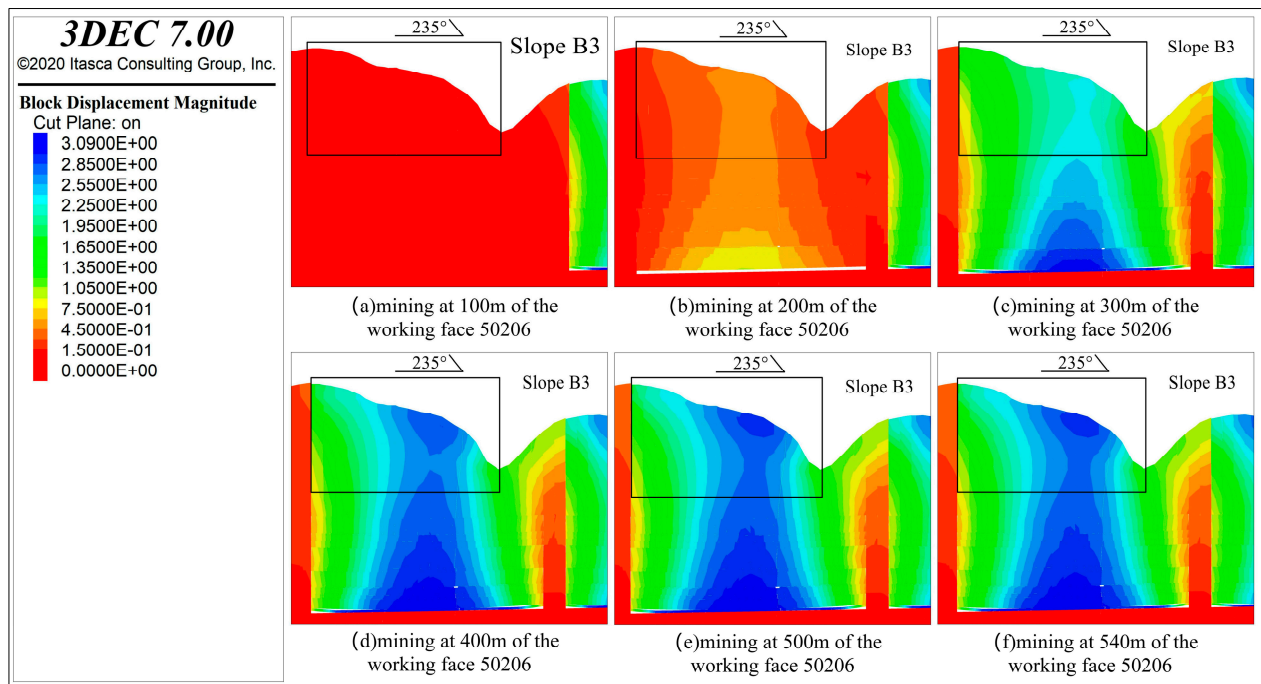


Figure 8. Deformation profile of Slope B3.

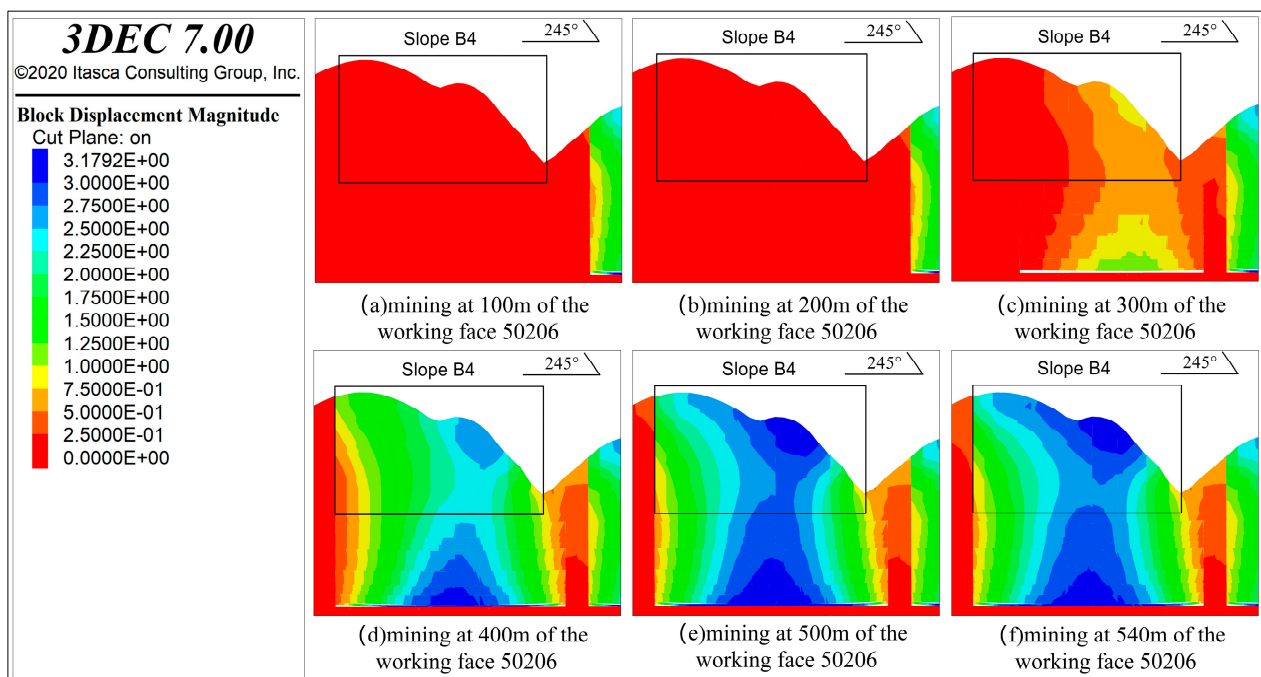


Figure 9. Deformation profile of Slope B4.

Block displacement slices were created along the L5 profile line, as shown in Figure 10. When the 50205 working face was mined to 100~300 m, no significant displacement response occurred inside the B5 slope, with a maximum displacement of 0.02 m (Figure 10a,b). When mining advanced to 500 m, obvious displacement appeared in the middle-lower part of the slope, with a maximum displacement of 2.75 m (Figure 10c). By the end of mining of the 50205 working face (540 m), deformation had become continuous in the middle-lower part of the slope, with a maximum deformation value of 3.08 m (Figure 10d). During the entire mining process of the 50206 working face, the deformation zone inside

the slope caused by mining of the 50205 working face further expanded northward, but the maximum deformation did not increase significantly (Figure 10e–h).

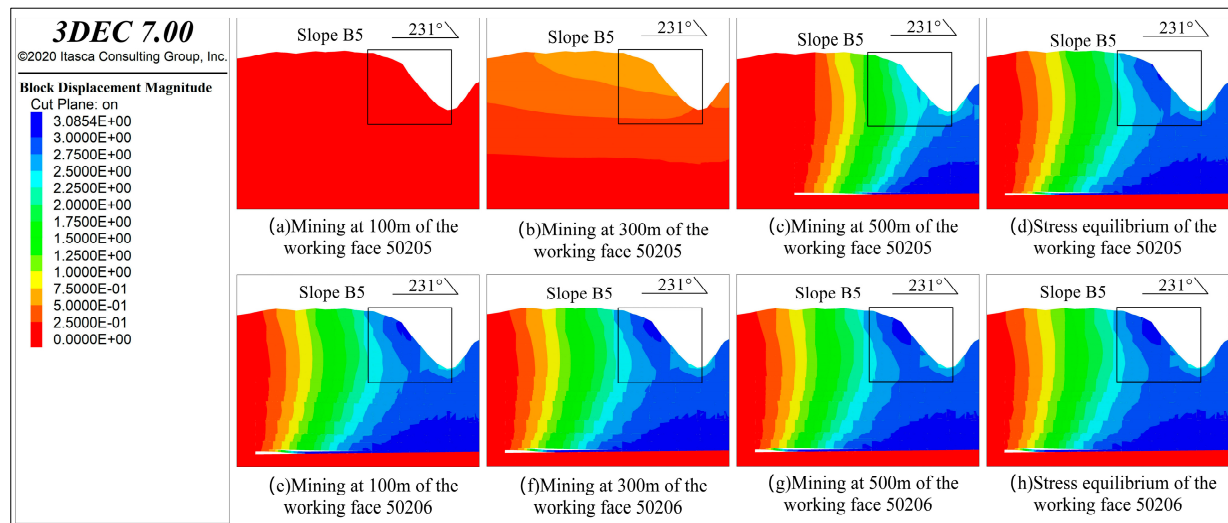


Figure 10. Deformation profile of Slope B5.

4.2. Temporal Characteristics of Slope Deformation Induced by Mining

By consulting the mining records of the 50205 and 50206 working faces at the Zhen'er Coal Mine, we established the relationship between excavation steps and actual calendar dates. Specifically, based on the recorded daily advance rate (approximately 3 m/day), each 10 m excavation step corresponds to a mining duration of about 3.3 days. The equilibrium state achieved at each step is regarded as representing the quasi-static deformation at the corresponding calendar date. On this basis, the deformation rates reported in mm/day are estimated by dividing the incremental block displacement between successive steps by the step duration and displacement–time curves of the monitoring points on five slopes were plotted using Origin 2021 software.

(1) Slope B1

The displacement–time curves of the slope surface monitoring points G1~G10 and the internal slope monitoring points U1~U6 of the B1 slope, along with the deformation values at key time points, are shown in Figure 11 and Table 4.

As can be seen from Figure 11 and Table 4, from January 2017 to December 2019, the deformation of all monitoring points on the surface and inside Slope B1 increased gradually. The deformation rate was relatively large in the early stage and gradually slowed down in the middle and late stages. Since most of Slope B1 is located above the 50205 working face, the deformation rate of the monitoring points on the slope surface during the mining of the 50205 working face was greater than that during the mining of the 50206 working face. For the surface monitoring points, point G8 near the slope toe had the maximum deformation rate of 14.858 mm/d during the mining of the 50205 working face; during the mining of the 50206 working face, the maximum deformation rate was 0.185 mm/d at point G2 at the slope crest. In the residual deformation stage of the 50205 working face, the maximum deformation amount was 10.37 mm at point G9 near the slope toe, while in the residual deformation stage of the 50206 working face, the maximum was 3.62 mm at point G1 at the slope crest. The maximum final deformation was 2.78 m at point G8 in the middle-lower part of the slope (where the curvature was greatest). During the mining of the 50205 working face, for the internal monitoring points, the maximum deformation rate was 1.239 mm/d at U3, and the maximum residual deformation value was 7.45 mm at U1. During the mining of the 50206 working face, the maximum deformation rate was

0.246 mm/d at U2, and the maximum residual deformation value was 2.58 mm at U1. The maximum final deformation inside the slope was 2.71 m at point U6. In the same period, a vertical comparison (G5~U3~U5) shows that the deformation on the slope surface was larger than that inside, and the deformation decreased with increasing depth. This indicates that the slope deformation is influenced not only by coal mining, but also by the self-weight gravity component of the slope.

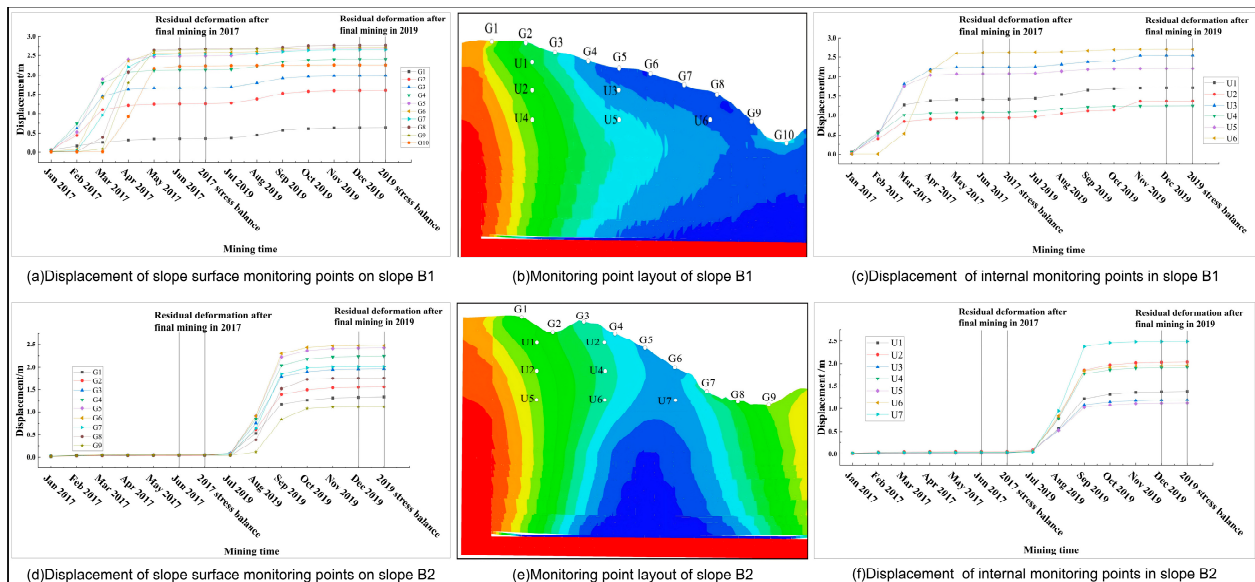


Figure 11. Locations of monitoring points on slopes B1 and B2 and displacement vs. time curves of individual monitoring points.

Table 4. Deformation statistics of Slope B1 monitoring points at key time points.

Monitoring Point	Deformation at End-January 2017/mm	Deformation at End-June 2017/mm	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50205 Working Face/mm	Deformation at End-July 2019/mm	Deformation at End-December 2019/mm	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50206 Working Face/mm	Final Deformation Value/m
G1	0.061	0.352	1.955	5.660	0.372	0.639	0.156	3.620	0.642
G2	0.063	1.258	6.986	4.390	1.282	1.594	0.185	2.920	1.597
G3	0.051	1.660	9.223	3.840	1.682	1.990	0.181	2.440	1.993
G4	0.039	2.131	11.837	3.870	2.147	2.405	0.150	1.950	2.407
G5	0.023	2.481	13.781	4.460	2.493	2.690	0.114	1.720	2.692
G6	0.017	2.573	14.295	7.050	2.588	2.726	0.081	1.490	2.727
G7	0.015	2.530	14.056	7.680	2.544	2.657	0.066	1.210	2.658
G8	0.014	2.674	14.858	9.510	2.691	2.779	0.053	0.670	2.780
G9	0.012	2.651	14.730	10.370	2.668	2.721	0.033	0.010	2.721
G10	0.008	2.229	12.382	9.550	2.243	2.257	0.011	0.400	2.257
U1	0.056	1.422	7.900	4.100	1.447	1.708	0.157	2.580	1.711
U2	0.048	0.932	5.178	3.630	0.959	1.378	0.246	2.130	1.381
U3	0.019	2.250	12.499	3.350	2.262	2.537	0.157	1.340	2.538
U4	0.053	1.083	6.014	3.550	1.109	1.256	0.095	1.930	1.258
U5	0.018	2.086	11.588	2.490	2.097	2.215	0.070	0.760	2.216
U6	0.012	2.620	14.557	7.450	2.634	2.709	0.045	0.550	2.710

(2) Slope B2

The displacement–time curves and deformation values at key time points for the surface monitoring points G1~G9 and the internal monitoring points U1~U7 on Slope B2 are shown in Figure 11 and Table 5.

Table 5. Deformation statistics of Slope B2 monitoring points at key time points.

Monitoring Point	Deformation at End-January 2017/m	Deformation at End-June 2017/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50205 Working Face/mm	Deformation at End-July 2019/m	Deformation at End-December 2019/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50206 Working Face/mm	Final Deformation Value/m
G1	0.015	0.038	0.212	0.47	0.081	1.332	7.184	10.440	1.342
G2	0.016	0.035	0.197	0.37	0.075	1.550	8.414	8.250	1.559
G3	0.020	0.055	0.305	0.66	0.089	1.961	10.587	7.460	1.969
G4	0.020	0.054	0.302	0.61	0.086	2.235	12.109	7.090	2.242
G5	0.021	0.052	0.291	0.53	0.078	2.415	13.121	6.770	2.422
G6	0.021	0.051	0.283	0.48	0.065	2.470	13.438	5.190	2.476
G7	0.019	0.043	0.242	0.37	0.046	2.011	10.931	2.160	2.014
G8	0.017	0.039	0.218	0.30	0.039	1.749	9.494	1.590	1.750
G9	0.015	0.043	0.241	0.33	0.039	1.105	5.897	1.850	1.107
U1	0.014	0.031	0.170	0.29	0.071	1.374	7.464	8.410	1.383
U2	0.020	0.052	0.291	0.57	0.085	2.028	10.971	7.320	2.035
U3	0.012	0.022	0.123	0.13	0.066	1.195	6.514	7.450	1.202
U4	0.017	0.035	0.195	0.28	0.068	1.911	10.420	7.040	1.918
U5	0.011	0.020	0.114	0.12	0.069	1.120	6.105	6.910	1.126
U6	0.015	0.028	0.157	0.19	0.063	1.958	10.719	6.550	1.964
U7	0.017	0.034	0.189	0.27	0.045	2.483	13.606	3.100	2.486

As can be seen from Figure 11 and Table 5, from January to June 2017, during the mining of the 50206 working face, the displacement values and deformation rates of all monitoring points on the surface and inside Slope B2 were relatively small, but not entirely zero. The maximum displacement was 0.055 m at surface point G3, with a deformation rate of 0.305 mm/d, indicating that the mining of the 50205 working face still had a certain influence on Slope B2, which is entirely located above the adjacent 50206 working face. From July to December 2019, during the mining of the 50206 working face, the displacement values of all monitoring points increased rapidly. The maximum deformation rate was observed at internal monitoring point U7, which is located near the strike main section of the 50206 working face, with its displacement reaching 2.483 m and a deformation rate of 13.606 mm/d. On the slope surface, the maximum displacement was 2.476 m at point G6 in the middle-lower part, and its deformation rate was 13.438 mm/d, the largest among the nine surface monitoring points; point G5 also had a relatively large deformation rate of 13.121 mm/d. In the residual deformation stage after mining, the maximum deformation was 10.44 mm at monitoring point G1 at the slope crest. The residual deformation amounts of the slope surface monitoring points were larger than those at the monitoring points in the gully at the slope toe. The maximum final deformation was 2.486 m at the internal monitoring point U7. In the same period, a vertical comparison (G1~U1~U2~U5) shows that the deformation on the slope surface was larger than that inside.

(3) Slope B3

The displacement–time curves and deformation values at key time points for the surface monitoring points G1~G10 and the internal monitoring points U1~U6 on Slope B3 are shown in Figure 12 and Table 6.

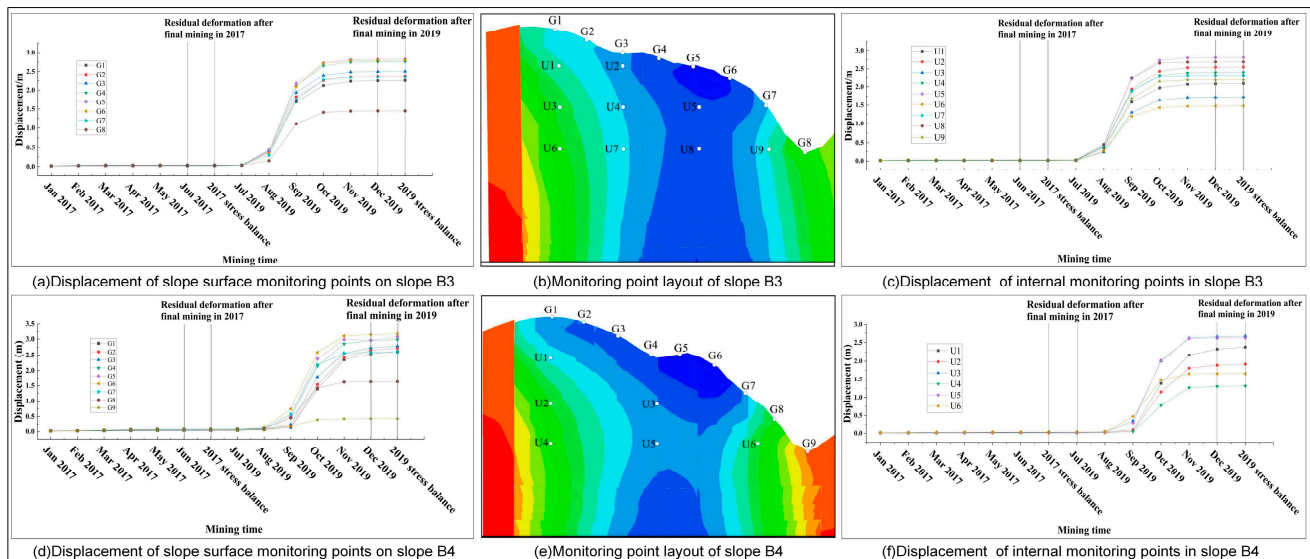


Figure 12. Locations of monitoring points on slopes B3 and B4 and displacement vs. time curves of individual monitoring points.

Table 6. Deformation statistics of Slope B3 monitoring points at key time points.

Monitoring Point	Deformation at End-January 2017/m	Deformation at End-June 2017/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50205 Working Face/mm	Deformation at End-July 2019/m	Deformation at End-December 2019/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50206 Working Face/mm	Final Deformation Value /m
G1	0.013	0.018	0.099	0.10	0.037	2.248	12.390	8.97	2.257
G2	0.014	0.019	0.106	0.10	0.031	2.371	13.064	7.53	2.378
G3	0.015	0.023	0.125	0.12	0.032	2.498	13.752	5.65	2.504
G4	0.016	0.027	0.148	0.14	0.034	2.758	15.176	5.41	2.764
G5	0.018	0.032	0.177	0.16	0.037	2.821	15.492	4.66	2.825
G6	0.018	0.034	0.191	0.18	0.036	2.796	15.343	3.57	2.800
G7	0.018	0.037	0.203	0.22	0.037	2.345	12.826	2.75	2.348
G8	0.016	0.038	0.209	0.29	0.035	1.448	7.836	1.79	1.450
U1	0.012	0.016	0.090	0.12	0.030	2.083	11.482	7.83	2.091
U2	0.015	0.023	0.125	0.12	0.032	2.542	13.998	5.98	2.548
U3	0.009	0.011	0.060	0.12	0.017	1.723	9.509	5.72	1.728
U4	0.014	0.020	0.110	0.13	0.025	2.398	13.210	4.16	2.402
U5	0.017	0.026	0.145	0.18	0.029	2.804	15.430	3.64	2.807
U6	0.008	0.009	0.052	0.11	0.016	1.476	8.145	3.64	1.479
U7	0.012	0.015	0.083	0.13	0.018	2.321	12.812	2.25	2.324
U8	0.015	0.022	0.121	0.18	0.023	2.683	14.784	1.56	2.685
U9	0.017	0.031	0.171	0.24	0.029	2.188	11.986	1.65	2.190

As can be seen from Figure 12 and Table 6, from January to June 2017, during the mining of the 50205 working face, the displacement values and deformation rates of all monitoring points on the surface and inside Slope B3 were relatively small, but not entirely zero. The maximum displacement was 0.037 m at point G7, which is located at the slope toe with relatively large curvature; the maximum deformation rate was 0.209 mm/d at

point G8 in the gully at the slope toe. This indicates that the mining of the 50205 working face still had a certain influence on Slope B3, which is entirely located above the adjacent 50206 working face. From July to December 2019, during the mining of the 50206 working face, the displacement values of all monitoring points increased rapidly. The maximum deformation rate occurred at surface monitoring point G5, which is located directly above the goaf and near the strike main section of the 50206 working face, with a displacement reaching 2.821 m and a deformation rate of 15.492 mm/d. The maximum displacement inside the slope was 2.804 m at point U5, which also had a relatively high deformation rate of 15.430 mm/d. In the residual deformation stage after mining, the maximum deformation was 8.97 mm at monitoring point G1 at the slope crest. The maximum final deformation was 2.826 m at surface point G5. In the same period, a vertical comparison (G5~U5~U8) shows that the deformation on the slope surface was larger than that inside, and it decreased with increasing depth.

(4) Slope B4

The displacement–time curves and deformation values at key time points for the surface monitoring points G1~G9 and the internal monitoring points U1~U7 on Slope B4 are shown in Figure 12 and Table 7.

Table 7. Deformation statistics of Slope B4 monitoring points at key time points.

Monitoring Point	Deformation at End-January 2017/m	Deformation at End-June 2017/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50205 Working Face/mm	Deformation at End-July 2019/m	Deformation at End-December 2019/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50206 Working Face/mm	Final Deformation Value /m
G1	0.015	0.030	0.169	0.81	0.034	2.546	13.970	66.11	2.612
G2	0.016	0.034	0.188	1.01	0.039	2.649	14.522	71.04	2.720
G3	0.016	0.037	0.205	0.99	0.042	2.729	14.948	57.2	2.786
G4	0.017	0.045	0.248	1.01	0.050	2.949	16.130	33.75	2.983
G5	0.018	0.063	0.351	1.08	0.069	2.960	16.086	112.59	3.072
G6	0.019	0.072	0.398	1.1	0.078	3.140	17.038	21.34	3.161
G7	0.019	0.075	0.416	1.07	0.080	2.591	13.975	14.78	2.606
G8	0.019	0.069	0.383	0.83	0.073	1.626	8.645	3.97	1.630
G9	0.013	0.047	0.261	0.41	0.046	0.426	2.101	1.73	0.427
U1	0.012	0.022	0.123	0.55	0.023	2.330	12.820	52.09	2.382
U2	0.009	0.014	0.078	0.32	0.012	1.891	10.428	28.73	1.920
U3	0.015	0.025	0.140	0.38	0.025	2.655	14.606	16.08	2.671
U4	0.007	0.010	0.058	0.28	0.009	1.303	7.180	13.67	1.317
U5	0.012	0.017	0.093	0.25	0.016	2.620	14.462	6.19	2.626
U6	0.016	0.033	0.181	0.35	0.033	1.659	9.036	1.59	1.661

As can be seen from Figure 12 and Table 7, from January to June 2017, during the mining of the 50205 working face, the displacement values and deformation rates of all monitoring points on the surface and inside Slope B4 were relatively small, but not entirely zero. The maximum displacement was 0.075 m at point G7, which is located near the slope toe, and the maximum deformation rate was also at G7, at 0.416 mm/d. This indicates that the mining of the 50205 working face still had a certain influence on Slope B4, which is entirely located above the adjacent 50206 working face. From July to December 2019, during the mining of the 50206 working face, the displacement values of all monitoring points increased rapidly. The maximum deformation rate occurred at surface monitoring point G6, which is located directly above the goaf and near the strike main section of the 50206 working face, with its displacement reaching 3.140 m and its deformation rate also

being the largest, at 17.038 mm/d. The maximum displacement inside the slope was at point U3, with a value of 2.655 m, and its deformation rate was also the largest, reaching 14.606 mm/d. In the residual deformation stage after mining, the maximum deformation was 112.59 mm at point G5. The maximum final deformation was 3.072 m at surface point G5. In the same period, a vertical comparison (G1~U1~U2~U4) shows that the deformation on the slope surface was larger than that inside, and it decreased with increasing depth.

(5) Slope B5

The displacement–time curves and deformation values at key time points for the surface monitoring points G1~G6 and the internal monitoring points U1~U6 on Slope B5 are shown in Figure 13 and Table 8.

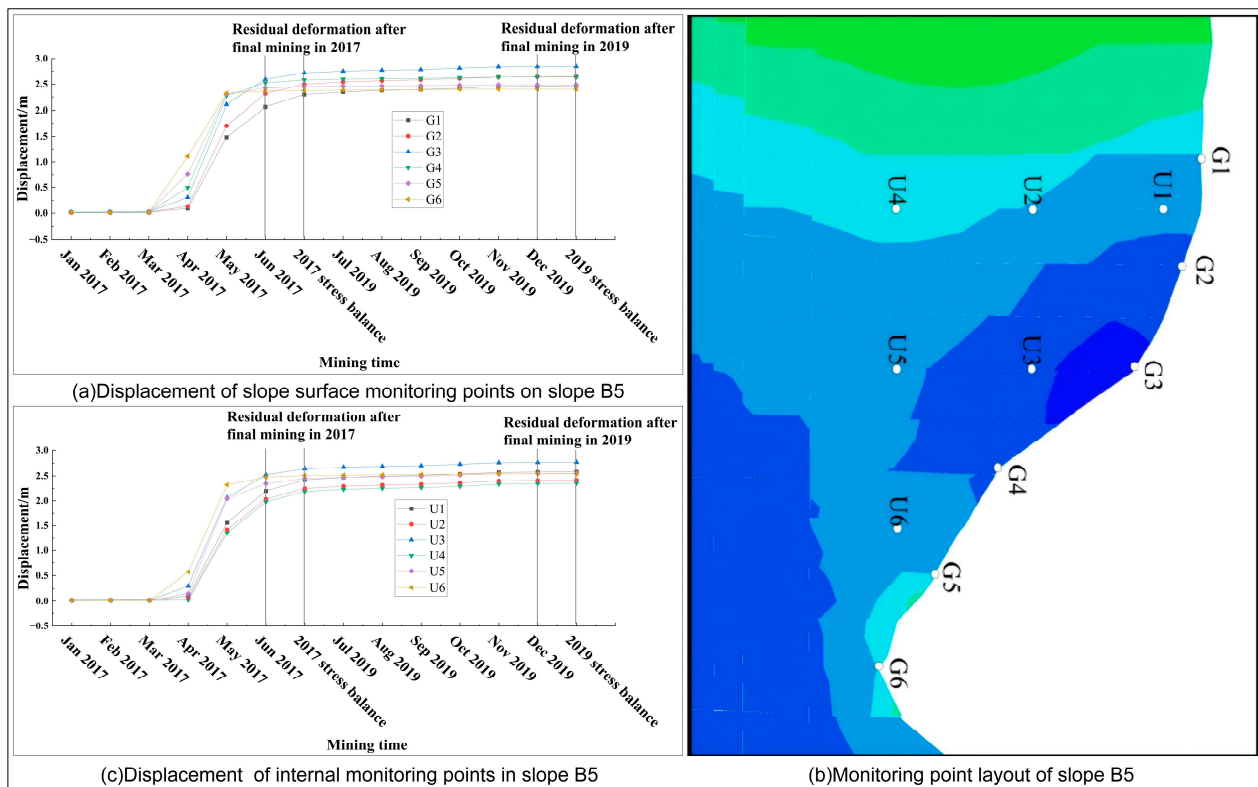


Figure 13. Locations of monitoring points on slopes B5 and displacement vs. time curves of individual monitoring points.

As can be seen from Figure 13 and Table 8, from January to June 2017, during the mining of the 50205 working face, the maximum displacement on the slope surface was 2.596 m at point G3, where the curvature was greatest, and its deformation rate was also the maximum, at 17.308 mm/d. Inside the slope, the maximum displacement was 2.526 m at point U3, with a maximum deformation rate of 16.837 mm/d; point U5 also experienced relatively large deformation. From July 2019 to December 2019, during the mining of the 50206 working face, the displacement at surface monitoring point G3 was also the maximum, reaching 2.845 m, but its deformation rate was not the maximum; the maximum rate was 0.905 mm/d at point G1. Inside the slope, the maximum displacement was 2.763 m at point U3, but the maximum deformation rate was 0.895 mm/d at monitoring point U2. In the residual deformation stage after mining, the maximum deformation was 7.62 mm at point U4. The maximum final deformation was 2.845 m at surface point G3. In the same period, a vertical comparison (G3~U3~U5) shows that the deformation on the slope surface was larger than that inside, and it decreased with increasing depth.

Table 8. Deformation statistics of Slope B5 monitoring points at key time points.

Monitoring Point	Deformation at End-January 2017/m	Deformation at End-June 2017/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50205 Working Face/mm	Deformation at End-July 2019/m	Deformation at End-December 2019/m	Deformation Rate /mm·d ⁻¹	Residual Deformation of 50206 Working Face/mm	Final Deformation Value /m
G1	0.017	2.065	13.766	233.600	2.350	2.461	0.905	6.15	2.468
G2	0.019	2.318	15.453	180.960	2.546	2.645	0.809	3.69	2.648
G3	0.019	2.596	17.308	123.390	2.755	2.843	0.684	2.19	2.845
G4	0.017	2.527	16.848	56.320	2.599	2.641	0.317	0.31	2.641
G5	0.012	2.427	16.181	25.220	2.461	2.488	0.196	−0.09	2.487
G6	0.008	2.370	15.798	9.560	2.384	2.402	0.127	−0.55	2.401
U1	0.018	2.197	14.648	222.810	2.469	2.579	0.884	5.46	2.585
U2	0.015	2.035	13.569	213.550	2.294	2.410	0.895	7.16	2.417
U3	0.017	2.526	16.837	117.380	2.674	2.763	0.666	3.23	2.766
U4	0.011	1.978	13.189	209.770	2.231	2.346	0.878	7.62	2.354
U5	0.011	2.347	15.647	101.530	2.473	2.547	0.549	3.47	2.551
U6	0.011	2.477	16.516	31.390	2.517	2.545	0.199	0.35	2.545

4.3. Field Investigation Validation

Due to the lack of on-site monitoring data and the steep terrain, which made field surveys extremely difficult, the UAV survey method was employed for verification and orthophoto images of the mining area (acquired on 15 November 2025) were used to identify fracture distribution, as shown in Figure 14.

Numerical simulation results show that deformation of slope B1 is mainly concentrated near the toe on the western side of the slope, with a high-deformation zone distributed in a band along the slope aspect (Figure 14a). Orthophoto crack identification reveals well-developed tensile cracks near the main section of working face 50205, with crack strikes generally consistent with the slope aspect, a maximum extension length of approximately 113 m, local slumping at the toe, and no obvious cracks at the trailing edge of the platform on the slope top. Cracks above the coal pillar are weak, and the surface integrity is relatively good (Figure 14b,c). The numerical simulation results are essentially consistent with the field investigation results. Numerical simulation shows that deformation of slope B2 is mainly concentrated in the middle and upper parts of the slope body, gradually expanding towards the slope top and the gully at the toe. Orthophoto images indicate that the upper and middle-upper parts of this slope are topographically broken, with cracks mainly distributed at the bottom of gullies and on ridge positions, and multiple shallow slumps are observable (Figure 14b,d), which are highly consistent with the locations of high deformation zones from numerical simulation. Numerical calculation shows that the middle-upper part and the southern slope face of slope B3 are the concentrated deformation zones. Crack identification results show that in the gully at the toe of the slope, cracks with strikes generally consistent with the slope aspect have developed, with a maximum extension length of approximately 120 m. Obvious slumping signs exist on the slope faces on both sides of the slope, with slumped soil accumulated in the gully (Figure 14b,e). Field investigation shows that two obvious cracks have developed in the southwestern part of slope B4, with crack strikes generally consistent with the slope aspect (Figure 14b,f), consistent with the deformation characteristics revealed by numerical simulation. Field investigation results of slope B5 show that on the slope above working face 50205, multiple cracks extending from the slope top to the toe have developed, ranging from 10 to 20 m in length, with a nearly north-south distribution. On the slope above working face 50206, no obvious large-area cracks are observed, but a transverse crack has developed at the junction

between the upper tableland and the slope face, extending into working face 50205 with a length of approximately 180 m (Figure 14b,g), which also shows good consistency with the numerical simulation deformation results.

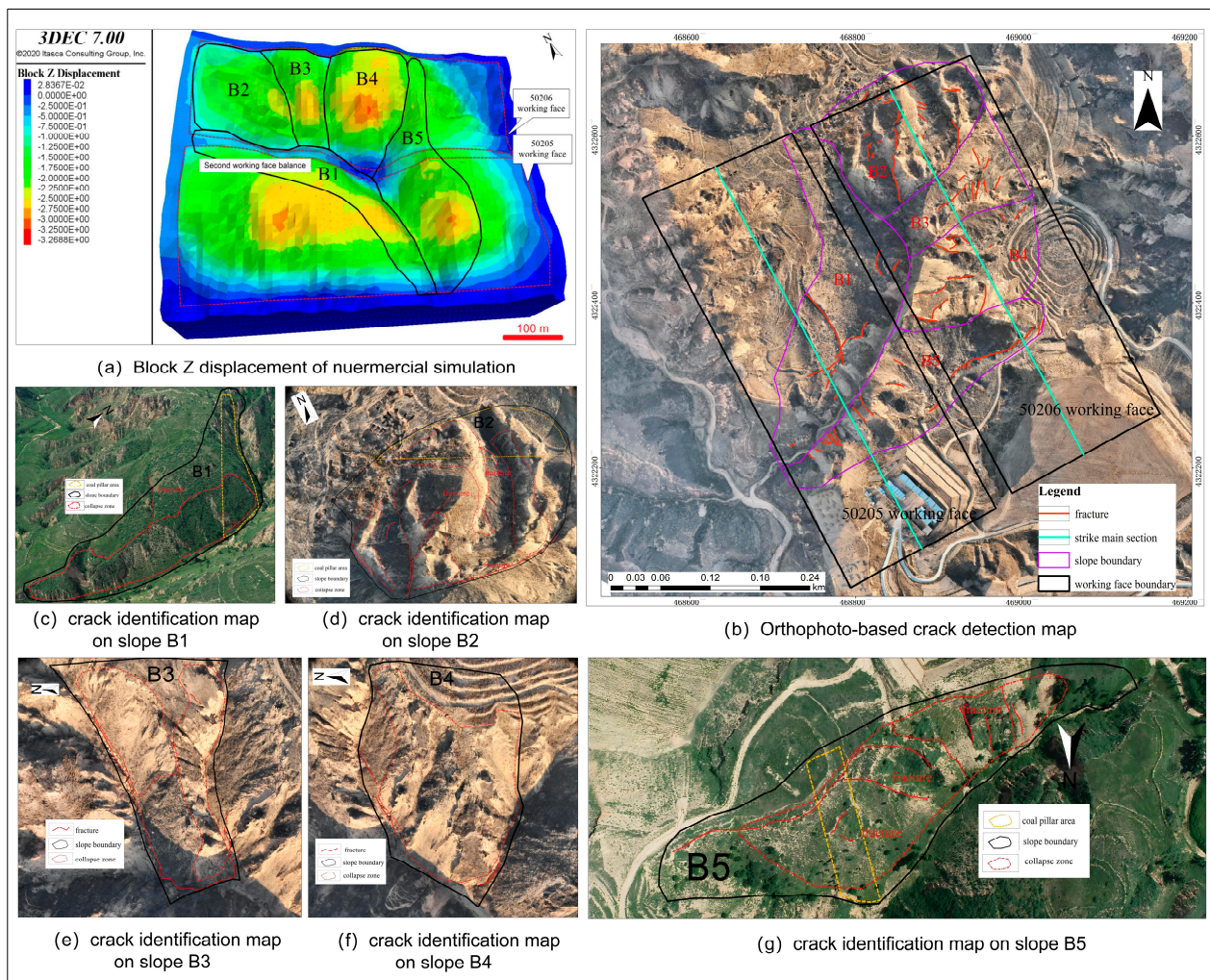


Figure 14. Distribution of fractures on the slope surface.

5. Discussion

5.1. Deformation Evolution Law of Mining-Affected Slopes

(1) Slope B1

On Slope B1, the slope surface deformation first appeared near the slope crest, then gradually extended to the middle and middle-lower parts as the working face advanced and continuously intensified around the subsidence center. After entering the significant deformation stage, the middle-lower part of the slope surface became the primary zone of deformation development, while the gully at the slope toe exhibited a certain lagging response. The internal deformation of the slope displayed a distribution pattern in which the upper part responded first, and the deformation gradually increased in the middle-lower part and transferred toward the slope surface. The high-value deformation zone was mainly located inside the slope above the center of the working face subsidence basin and migrated as the center of the subsidence basin moved.

The temporal evolution pattern of deformation on Slope B1 was characterized by no obvious response in the early stage, rapid development in the middle stage, a tendency to stabilize in the late stage, and re-disturbance by the adjacent working face. The mining of the adjacent working face still had a certain influence on the slope above the old goaf.

Analysis of displacement–time curves (Figure 11) shows that, even after accounting for the spatial offset between the working face and the slope, a distinct temporal lag persists at the slope toe: the deformation there continues to increase for a period after the face has passed, reflecting the time-dependent compaction of caved rocks and stress redistribution. This lagging behavior is consistent with published time-settlement observations under similar mining and geological conditions [2,3] (Guo, 2015 and Yu, 2012).

(2) Slope B2

Slope B2 is located above the open-off cut. The slope surface deformation exhibited a spatial distribution pattern characterized by rapid initiation, development first in the middle part, followed by expansion to the entire slope surface and migration toward the slope toe. The internal deformation characteristics of Slope B2 were as follows: controlled by the subsidence center, deformation first developed in the middle part and gradually expanded toward the slope toe along the interior of the slope. After the working face advanced beneath the slope, the internal deformation responded rapidly in the middle part of the slope, and the existing high-value zone slowly migrated toward the slope toe as mining advanced.

The temporal evolution pattern of slope surface deformation on Slope B2 was characterized by small deformation in the early stage of mining, rapid increase in the middle stage, and slow stabilization in the late stage, controlled by the development process of the subsidence basin. The temporal evolution pattern of internal deformation on Slope B2 can be summarized as follows: mining influence was transmitted to the interior of the slope through overburden collapse, generating relatively large displacement within a short period, with the characteristics of rapid transmission and concentrated expansion. Although the internal deformation initiates rapidly, the displacement–time curves (Figure 11) reveal that the surface deformation near the slope toe exhibits a time lag relative to the face position. This delay is primarily attributed to the progressive compaction of the caved zone and the time-dependent transfer of stress from the collapsed strata to the slope mass, rather than solely to the mining geometry.

(3) Slope B3

The slope surface deformation of Slope B3 generally showed that deformation occurred first at the gully at the slope toe and then expanded toward the middle part and the ridge, with the high-value zone mainly appearing in the middle region. Since Slope B3 is located in the middle part of the 50206 working face, the internal deformation of the slope was small in the early stage of mining, exhibiting a pattern of relatively weak early response, initial development in the middle part, and rapid intensification after the overburden collapse.

The rapid expansion of slope surface displacement on Slope B3 mainly occurred in the middle stage of mining. In the late stage of mining, the increase in deformation was significantly weakened. The internal deformation was characterized by a sharp increase within a relatively short period. Based on the displacement–time curves (Figure 12), the lag phenomenon on Slope B3 is less pronounced than on some other slopes because of its location above the central part of the working face. Nevertheless, a careful examination of the curves indicates that the deformation continues to develop for a short period after the face has passed beneath the slope, which confirms the contribution of time-dependent caved rock compaction to the overall deformation pattern. The comparison with documented time-settlement data from central regions of the working face supports this interpretation.

(4) Slope B4

The slope surface deformation of Slope B4 generally showed that the gully at the slope toe responded first and formed a high-value zone, which then shifted to the middle part and expanded toward the slope crest. The internal deformation of the slope generally exhibited a pattern of weak early response, initial development in the middle part, and

subsequent expansion toward the upper and lower parts of the slope. During the early to middle stage of the working face advance, the response was weak; in the middle stage, the displacement increased rapidly, and then gradually transitioned into a state of slow increase. The displacement–time curves (Figure 12) demonstrate that the slope toe initially responds, yet the full development of deformation in the middle and upper parts follows with a certain time lag. This sequence supports the interpretation that the lag is influenced not only by the direction of face advance but also by the time required for the caved rocks to compact and transmit sufficient support loss to the overlying slope.

(5) Slope B5

Slope B5 spans two working faces and is located at the tail end of their advance direction. The deformation overall showed a lagging response in the early stage, gradually increased with the sequential mining of the two working faces, and converged toward the subsidence center of the working faces. In the initial stage, the deformation was mainly controlled by the 50205 working face, with high-value deformation zones concentrated near the subsidence center of the 50205 working face and at the topographic turning parts of the slope surface. With the mining of the 50206 working face, the mining influences of the two working faces gradually superimposed, and the slope surface deformation expanded from a previously relatively independent distribution state to the middle region.

The rapid increase in slope surface deformation on Slope B5 occurred in the middle to late stages of mining of the 50205 and 50206 working faces, while the deformation was slow in the early to middle stages. After the 50205 face had passed, the deformation continued to accumulate for a notable period, and a second stage of delayed acceleration occurred after the 50206 face advanced. This phased lag is attributed to the superimposed effects of time-dependent compaction in both goaf areas and the gradual redistribution of stress toward the slope mass. The observed behavior agrees well with published time-settlement records (Figure 13) from double working face districts, lending further credibility to the modeled time-lag characteristics.

5.2. Influencing Factors of Deformation of Mining-Affected Slopes

The underground goaf created by mining is the core driving force for slope deformation and instability, and it is also influenced by factors such as the spatial position relationship between the working face and the slope (the angle with the mining direction), slope gradient, slope aspect, slope height, and slope shape. Concave slopes (B2) are dominated by toppling failure and subsidence, and their maximum deformation is greater than that of convex and linear slopes. On convex slopes (B1, B3, B4), the high-value deformation zones are distributed in the areas of maximum curvature.

The deformation of mining-affected slopes that span working faces is more complex (Slope B5). For example, on slopes located at the open-off cut (Slope B2), deformation initiates rapidly, while the farther from the open-off cut, the slower the initiation.

The angle between the slope aspect of Slope B3 and the mining direction is 80° , close to 90° , which corresponds to a cross-slope mining condition. The slope is subjected to a “sandwich”-type compressive state, resulting in a more complex deformation mechanism, with both tensile deformation and thrust-type deformation occurring simultaneously and a faster deformation rate. The angle between the slope aspect of Slope B4 and the mining direction is 100° , also close to 90° , and its deformation mechanism is basically similar to that of Slope B3. For Slope B5, the angle between the slope aspect and the mining direction is 170° , representing an up-slope mining condition, where tensile fractures develop and toppling collapse may occur toward the gully at the slope toe. The slope aspects of Slopes B1 and B2 intersect obliquely with the mining direction, falling between down-slope mining

(angle close to 0°) and cross-slope mining; tensile fractures dominate, and the deformation is mainly characterized by toppling toward the goaf.

The larger the slope gradient, the greater the mining-induced deformation amount and the larger the proportion of the slope area experiencing deformation. For instance, the maximum deformation of Slopes B1 and B2 is greater than that of Slopes B3, B4, and B5.

The sunny slopes (B1/B2) have relatively well-developed vegetation. Their plant roots provide anchoring and reinforcement effects, effectively increasing the shear strength of the slope's rock and soil mass. Consequently, the maximum slope surface deformation on the sunny slopes is slightly smaller than that on the shady slopes (B3/B4/B5). Therefore, slope aspect has a certain influence on the magnitude of surface deformation of mining-affected slopes.

5.3. Deformation and Failure Mechanism of Mining-Affected Slopes

Based on a systematic analysis of the deformation evolution patterns of five typical mining-affected slopes (B1–B5) above working faces 50205 and 50206 in the Zhen'er coalfield, the deformation and failure mechanism can be summarized as a progressive, time-dependent process driven by the coupling of overburden movement and slope topography. As the coal seam is extracted, sequential caving, fracturing and sagging of the strata initiate stress redistribution (Figure 15), with deformation first appearing inside the slope above the subsidence centre and then propagating toward the surface and the toe. As can be seen from Figure 15, the ZZ stress field of the rock mass surrounding the goaf undergoes significant changes, forming distinct zones: a stress-reduced zone (the goaf area) and a stress-concentrated zone (in front of the coal wall and on both sides). As observed from Figure 15c–f, with the expansion of the excavation range, the original stress equilibrium of the overlying strata is disrupted. Under the combined effects of gravity and concentrated stress, the rock layers fracture, separate (bed separation), and gradually cave downward to fill the goaf. This process gives rise to the development of the classic 'three zones' (the caving zone, the fractured zone, and the continuous bending subsidence zone), eventually resulting in the formation of a surface subsidence basin and the deformation and failure of the overlying slope above the working face.

Spatially, the initiation point and propagation path vary with the slope's position relative to the working face: slope B2 above the open-off cut responds rapidly from its middle part; slope B3 above the central panel first deforms at the gully toe; and slope B5 spanning two panels experiences superimposed deformation that converges toward the middle. Temporally, all slopes exhibit a three-stage pattern of weak early response, rapid mid-stage development and late slow stabilization, often with renewed disturbance by adjacent panels. Most critically, a pronounced time lag is observed: even after the face has passed, deformation at the toe or middle-lower part continues to increase, driven by the time-dependent compaction of caved rocks and the delayed transfer of mining-induced stress into the slope mass. This progressive accumulation ultimately manifests as a combination of tension cracks at the crest, shear sliding within the slope, and compressive heaving at the toe.

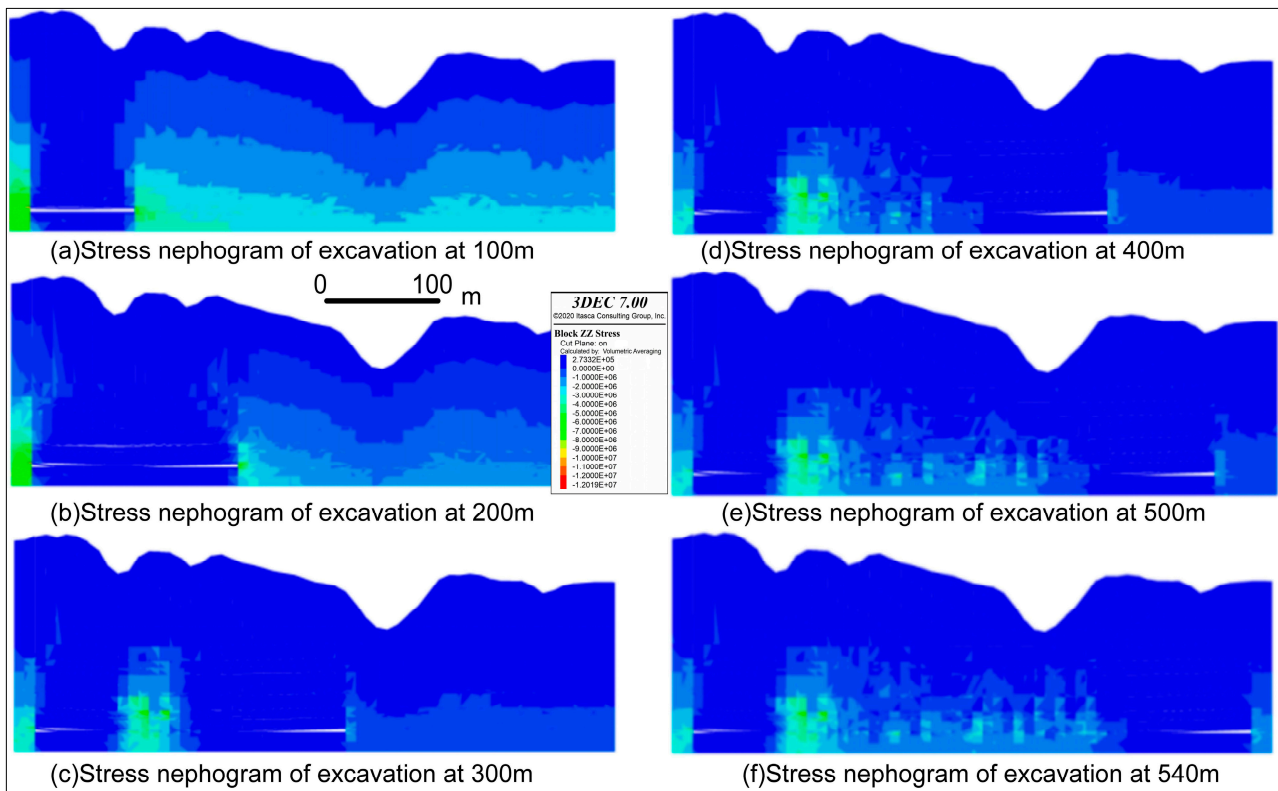


Figure 15. Block ZZ stress slice on the main section of working face 50205.

The magnitude and mode of failure are further controlled by the slope-mining geometry, slope shape, gradient and aspect. The angle between the slope aspect and the mining direction dictates the stress regime: near 90° cross-slope mining (B3, B4) subjects the slope to a ‘sandwich’ compression, producing simultaneous tension and thrust with rapid deformation rates; up-slope mining ($\sim 170^\circ$, B5) promotes tension cracks and toppling toward the gully; and oblique intersections (B1, B2) are dominated by tension-induced toppling into the goaf. Concave slopes (B2) exhibit larger subsidence and toppling failure than convex or linear slopes, while on convex slopes high deformation concentrates in zones of maximum curvature. Steeper slopes consistently suffer greater deformation and larger affected areas. Additionally, slope aspect exerts an indirect influence through vegetation: sunny slopes (B1/B2) with well-developed root systems show slightly smaller maximum deformation than shady slopes (B3/B4/B5), owing to the reinforcement of shear strength by roots. Together, these factors govern the progressive, time-dependent failure of mining-affected slopes.

6. Conclusions

(1) No matter what type of slope, coal mining will increase the amount of slope deformation. How mining-induced slope deformation evolves over time, which parts of the slope are deforming spatially, and what factors drive the deformation are the most fundamental questions that need to be answered in research on mining-induced slope deformation.

(2) On slope B1, surface deformation first peaked at 0.75 m at the crest (advance 100–200 m), later increased to 2.75 m at the crest, and reached 3.128 m near the toe when the working face reached 500 m. The northern gully remained <0.25 m during the working face 50205 extraction, then increased to 0.50 m (working face 50206 at 200 m) and stabilized at ~ 1 m above the coal pillar through the end of mining. Slope B2 experienced almost no deformation during mining of the working face 50205. During the working face 50206 extraction, significant

deformation initiated early above the open-off cut, with 0.50–0.75 m at the northwest corner; at 200 m advance, central slope surface displacements reached 0.50–1.00 m; as mining progressed to 300–400 m, deformation spread to the entire slope and toward the toe, reaching 0.75–2.48 m; and in the later stage (500–540 m), the pattern stabilized with slow increases along existing high-value zones, giving final displacements of 0.75–2.70 m. As mining advanced, surface deformation on slope B3 gradually intensified: at 100 m advance, no obvious displacement was observed on the slope surface; at 200 m, deformation first appeared at the gully at the slope toe with a maximum displacement of 0.75 m; at 300–400 m, deformation covered the entire slope, reaching 3.00 m at the western ridge; at 500–540 m, the maximum at the western ridge reached 3.27 m, while that at the north and south gullies was relatively smaller but still reached 1.50 m. At 100–200 m advance of the working face, no obvious surface displacement was observed on slope B4. At 300 m, deformation began to appear in the northern part of the slope surface, with a maximum displacement of 1.50 m. At 400 m, a high-deformation zone formed in the northern area, reaching a maximum of 3.00 m at protruding parts and gully incision zones; in the later stage (500–540 m), deformation covered the entire slope, with displacements ranging from 0.5 m to 3.27 m, and the high-deformation zone gradually shifted toward the central part, mainly concentrated in areas with significant topographic relief. During the working face 50205 extraction, surface deformation in the west of slope B5 reached 3.13 m at the gentle-steep transition. During early mining of the working face 50206, the west had residual deformation up to 3.18 m, while the east had none. In the middle-late stages, the east deformed 0–2.25 m (small on coal pillar, max in south) and the west increased to 3.27 m.

(3) Along the L1 profile, the internal deformation of the slope B1 gradually intensified with mining advance. At an advance of 100 m of the working face 50205, only slight subsidence (0.15 m) occurred above the open-off cut. During 200–400 m, displacement concentrated toward the central part and extended upward to the slope surface, with the maximum displacement increasing from 1.35 m to 3.01 m. After 500 m, the maximum displacement remained largely stable, but deformation at the slope toe and the lower part increased notably. Along the L2 profile, slope B2 internal deformation: none at 100 m; 1.05 m at the central part at 200 m; 1.05–2.55 m over the whole slope at 300 m; basically stable at 400–540 m, with slight expansion of the high-value zone. Along the L3 profile: no deformation at 100 m advance; weak response in the central part at 200 m with a maximum of 0.75 m; at 300–400 m, a high-value zone (2.85 m) formed in the central part and migrated upward; at 500–540 m, the high-value zone increased to 3.09 m, with no significant change of the slope B3 internal deformation. Along the L4 profile: no deformation at 100–200 m advance of the working face 50206; at 300 m, internal displacement of 1.00 m appeared in the middle-lower part; at 400–540 m, the central part increased to 3.17 m and extended toward the slope toe and upper part, while displacement on the lower steep slope did not increase significantly. Along L5, B5 slope: no notable deformation (0.02 m) at 100–300 m (working face 50205); 2.75 m at 500 m; and continuous 3.08 m at 540 m in the middle-lower part. During face 50206 mining, the internal deformation zone expanded northward, but the maximum did not increase significantly.

(4) From January 2017 to December 2019, deformation rates on slope B1 during the working face 50205 mining were higher than in 50206, with early high rates then slowing. Surface peak: rate 14.858 mm/d, residual 10.37 mm, and final 2.78 m (toe/mid-lower). Internal peak: rate 1.239 mm/d, residual 7.45 mm, and final 2.71 m. Deformation decreased with depth, due to mining and gravity. In early 2017, displacements on slope B2 were small (max 0.055 m at G3, rate 0.305 mm/d) due to residual effects from face 50205. In late 2019, peak rates occurred at U7 (2.483 m, 13.606 mm/d) and G6 (2.476 m, 13.438 mm/d); the residual deformation maximum was 10.44 mm at G1, and the final maximum was 2.486 m at U7.

Surface deformation was consistently larger than internal deformation. In early 2017, small displacements (max 0.037 m at G7, max rate 0.209 mm/d at G8) on B3. In late 2019, rapid increases occurred, with peak surface displacement 2.821 m and rate 15.492 mm/d at G5, and internal maximum 2.804 m at U5. Residual max was 8.97 mm at G1, and final max was 2.826 m at G5. Surface deformation exceeded internal deformation and decreased with depth. In early 2017, displacements were small (max 0.075 m at G7, rate 0.416 mm/d) on B4. In late 2019, rapid increases occurred, with a surface peak at G6 (3.140 m, 17.038 mm/d) and an internal peak at U3 (2.655 m, 14.606 mm/d). Residual max was 112.59 mm at G5, final max 3.072 m at G5, and surface deformation exceeded internal deformation and decreased with depth. During working face 50205 mining (January–June 2017), maximum surface deformation on slope B5 was 2.596 m at G3 (rate 17.308 mm/d), maximum internal deformation was 2.526 m at U3 (rate 16.837 mm/d), with U5 also large. During working face 50206 mining (July–December 2019), surface max remained at G3 (2.845 m), but maximum rate was 0.905 mm/d at G1; internal maximum at U3 (2.763 m) and maximum rate at U2 (0.895 mm/d). Residual max was 7.62 mm at U4, and final maximum was 2.845 m at G3. Surface deformation exceeded internal deformation and decreased with depth.

(4) The deformation of a mining slope is essentially the result of the coupling between overburden movement above the mined-out area and the slope topography. Mining-affected slope deformation is controlled not only by mining activities but also by factors such as slope shape, slope aspect, slope gradient, and slope height. Mining-affected slope deformation exhibits a time lag. The temporal evolution of slope deformation (B1, B5) above working face 50205 can be described as: initiation lag, slow accumulation, a brief period of stabilization, and then renewed intensification after the adjacent working face 50206 is mined. In contrast, the slopes (B2, B3, B4) above working face 50206 show rapid initiation, fast development, and continuous accumulation in the later stage, albeit with a decreasing rate of increase.

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