Numerical Simulation of Underground Mining-Induced Fault-Influenced Rock Movement and Its Application

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Abstract: The F317 fault, as a major tectonic zone in the Jianshan mine area, influences the geotectonic features and geomechanical properties of the mine area. Mining operations need to be conducted within these tectonic systems, so it is important to fully study and understand the characteristics and evolution of these tectonic systems to develop reasonable mining plans and safety measures. Aiming at the problem that the existence of the F317 fault affects the stability of the west road during the mining of the security pillar at The Jianshan underground mine in Panzhihua Iron Mine, the mechanical model of the fault surface was established through the theory of material mechanics. The mechanical criterion of fault slip during the security pillar retrieval process was obtained and combined with the contact surface theory in the numerical analysis software FLAC³D. Two numerical calculation models with and without the F317 fault were established to analyze the change characteristics of the maximum tensile stress and displacement of the road protection zone under different simulation scenarios. The influence of the fault’s presence on the surface road’s stability during the security pillar retrieval process was obtained. The study results show that changes in positive and shear stresses at the fault face caused by the security pillar retrieval process are the main factors influencing the fault slip. The upper side of the fault tends to slip along the fault face during the security pillar retrieval process, which theoretically prevents the transfer of subsidence displacement caused by underground mining to the roadside (foot side of the fault). The presence of the F317 fault has less effect on the tensile stresses at the road protection zone. Still, the fault allows the tensile stresses to be concentrated at the top and bottom of the quarry and at the isolated pillar, which is more likely to cause the rock to be stretched and squeezed. Without the F317 fault, the maximum subsidence displacement at the road protection zone is 30.59 mm, the maximum X-directional displacement is 42.17 mm (both of which are greater than the safe displacement limit by 20 mm), and the maximum Y-directional displacement is 19.75 mm, which is less than the safe displacement limit by 20 mm. Compared with the case without the F317 fault, the displacement at the road protection zone with the F317 fault is smaller, with a maximum subsidence displacement of 16.92 mm, a maximum X-directional displacement of 19.63 mm, and a maximum Y-directional displacement of 3.35 mm, all of which are less than the safe displacement limits. Therefore, the presence of the F317 fault provides some protection to the west side of the road from collapse due to underground mining.

Keywords: safety pillar; fault slide; contact surface; numerical simulation

1. Introduction

Faults can have a significant impact on the status of an ore body during mining. Faults can cause displacement of the ore body, leading to changes in its shape, size, and orientation. This can make it more difficult to access the ore and can also affect the stability of the surrounding rock. Faults can act as conduits for fluids, which can alter the mineralogy and chemistry of the surrounding rock [1,2]. This can lead to the formation of new minerals, the destruction of existing minerals, or the mobilization of metals and other elements. Faults can also be sites of mineralization, where ore deposits accumulate. In some cases, the
ore body may be localized along the fault zone, making it easier to extract. However, faults can also be a source of contamination, as fluids flowing through the fault can carry metals and other contaminants into the surrounding rock [3]. Faults can affect the stability of the mine workings, particularly if they are associated with seismic activity or other forms of ground movement [4]. This can pose a risk to the safety of workers and equipment and can also lead to production losses due to downtime.

Panzhihua Iron Mine is one of the four major monolithic iron ore deposits in China, located at the junction of Yanbian and Miyi counties in Panzhihua, Sichuan Province. The resource reserves are abundant. The Jianshan underground mine is an important part of the Panzhihua Iron Mine, located in Jianshan Town, Yanbian County, Panzhihua City, Sichuan Province and is one of the key projects of the Panzhihua Iron and Steel Group Company. The F317 fault is a major fault in the Jianshan underground mine in Panzhihua, China, its location being between underground mining and the surface road. The F317 fault zone has a significant impact on the stability of the surrounding rock mass in the Panzhihua Jianshan underground mine. The fault zone is a weak structural zone, which is prone to sliding and deformation, and it has a significant influence on the deformation and failure of the surrounding rock mass. The deformation and failure characteristics of the rock mass are closely related to the fault zone and the stability of the surrounding rock mass is affected by the deformation and failure of the fault zone. Overall, the F317 fault has had a significant impact on underground mining at the Jianshan mine, affecting the accessibility, stability, and mineralization of the ore body. Understanding the characteristics and behavior of the fault is crucial for safe and efficient mining operations in the area.

The study of mining-induced subduction fault mechanics is an important area of research in mining engineering and geomechanics. In recent years, a number of scholars have published research on this topic, with findings that have important implications for the design and operation of mining projects [5–8]. Bao et al. [9], to effectively monitor and control the severe mining-induced rockburst in deep fault areas, the fault activation law and the mechanical essence of rockburst induced by crossing fault mining were studied through theoretical analysis, microseismic monitoring, field investigation, and other methods; numerical simulation was employed to verify the obtained fault activation law and the mechanical nature. Finally, the prevention and treatment concepts of fault-type rockburst were proposed. Ding et al. [10], to effectively monitor and control the severe mining-induced rockburst in deep fault areas, the fault activation law and the mechanical essence of rockburst induced by crossing fault mining were studied through theoretical analysis, microseismic monitoring, field investigation, and other methods; numerical simulation was employed to verify the obtained fault activation law and the mechanical nature. In addition, a numerical model was constructed based on the geometry of the ore body and a major fault. The analysis of the model revealed three failure mechanisms acting during different stages of destruction: double-sided embedded beam deformation, fault activation, and cantilever-articulated rock beam failure. Wang et al. [11] studied the movement and rotation of the roof strata, which are influenced by a complex interaction between two faults in its strike direction of panel 31,100 of no. 1 mine in Pingdingshan, China. Mining-induced stress distribution and lateral roof roadway deformation mechanisms during fault population activation were investigated by both theoretical analysis and 3D numerical simulations. Bai et al. [12] summarized the “spatial and temporal intensity” correlation between excavation, fault, diagonal, and back-slip structures at the mine site in the context of blasting accidents that occurred near mining-induced sliding faults under high stress conditions. The results demonstrate that the coal burst triggered by the fault-slip instability under high-stress conditions is closely related to the excavation disturbance and the fold structure. Mining activities trigger the unloading and activation of the discontinuous structural surface of the fault, the rotation of the stress field, and the release of a large amount of elastic strain energy and cause dynamic disasters such as coal bursts.

The influence of faults in the study of slope stability has also been studied extensively in China and abroad [13–15]. Chen et al. [16] integrate the random finite difference method
(RFDM) into a probabilistic assessment framework and adopt general spatial variability and a cohesive-frictional soil slope example for illustration to quantitatively evaluate the response of slope failure related to anisotropic spatial variability of soil properties and reveal the underlying influence of anisotropic spatial variability of soil properties on the slope reliability. The results show that the directional angles of scales of fluctuation of general anisotropic spatial variability significantly affect the slope failure probability. Dong et al. [17] found that there is not only toppling deformation but also faults and other geological structures in the toppling deformation rock slope. They analyzed the relationship between the depth of overturning deformation and the location of the fault using the three-dimensional discrete element method, based on a field investigation of reverse-sloping rocky slopes along the fault. Mohammad et al. [18] present the results of a study on the effects of the ground surface geometry on the propagation of dip-slip faulting through granular soils, using a GPU-based DEM methodology that incorporates rolling resistance. The findings of the study show that the average slope of the rupture, regardless of the faulting type, faulting angle, and ground surface geometry, is equal to the corresponding average slope of the zero-extension line along the rupture.

National and international research on the impact of faults in the mining process is well documented in the mining industry [19–22]. Among them, Cao, Yongsheng, Yu, and Qinglei developed a numerical model with complex stratigraphic and geological conditions using the Dagushan Iron Mine as an engineering case study, analyzed the movement mechanism of faults in step excavation, and elucidated the deformation and stress evolution of rocky slopes in the roadway–landslide system as well as the fracturing process of concrete liners [23–26]. Wang et al. [25] present a novel method to simulate sandstone with any shaped mineral particles and investigate the effects of external factors (confining pressure and temperature) and internal factors (particle shape and internal structure) on the thermal cracking responses of sandstone. Zhu et al. [27] analyzed the stress state and mechanical response of the faulted surrounding rock system during mining based on the “masonry beam” theory and obtained the relationship between fault slip instability and the breakage of the overburden “key layer” and the advance of the quarry. Wang et al. [28] used the FLAC3D numerical calculation method to establish a calculation model containing the fault, studied its stability mechanism, analyzed the change of stress state and distribution pattern of the surrounding rock, and derived the stability mechanism of the surrounding rock supported by anchor rods in the broken surrounding rock roadway near the fault. They analyzed the pressure distribution law of the mine near the fault through a numerical simulation study and concluded that the positive stress change at the fault face is always earlier than the shear stress and the closer the working face is to the fault, or when the footplate is mined, the higher the risk of fault slippage. Pan [29] found, through similar simulation experiments, that the mining of the working face had a significant disturbing effect on the fault and the amount and rate of fault slip increased rapidly after the fault-initiated slip.

This study takes the Jianshan Iron Mine as the engineering background to establish a theoretical analysis model of faults and then intends to numerically simulate the impact of faults on the surface road during underground mining. The maximum tensile stress and subsidence displacement of the road protection zone are selected as indicators to measure the stability of the road protection zone under two conditions of the presence or absence of faults, to determine the impact of the presence of faults, and to verify the scientificity of the results in conjunction with the actual situation, to realize a reasonable solution for fault simulation and thus reduce the circle of security pillars, improve the mining resources extraction, and bring great economic benefits to the mine.

2. Overview of the Study Area

2.1. Overview of the Mine Site

The Jianshan underground mine is located in the eastern part of Panzhihua City, Sichuan Province. The ore is a medium grade, high sulfur, and low phosphorus vanadium...
and titanium magnetite ore, rich in vanadium and titanium resources and of high mining value. The ore body is orientated nearly east-west and tilts north, with a dip angle of 50° to 60°. The ore body is monoclinic, stratiform, and lenticular in shape. There are four ore belts: VIII, VII, VI, and V. Of all the belts, the VIII ore belt is the richest in ore and the largest in size, the VI ore belt is larger and of medium grade, and, although the V and VII ore belts are not small in size, they are of low grade and consist mainly of poor ore [30].

The mining method used is the bottomless column segmental crumbling method and the segmental rock drilling stage after filling mining method, because the deep ore body is above the existence of two sections of the Panzhihua toms outlet road, located in the northern part of the body and the western part of the ore body, as well as the surface part of the building structures away from the mining rock layer movement range is closer, taking into account (considering the safety of the road and surface structures as well as the stability of the open pit slope) a large number of deep ore bodies were left behind as security pillars, so now the deep security pillars will face complex mining geology when they are remined. Production at the mine site is shown in Figure 1.

![Figure 1. Production at the mine site.](image1)

### 2.2. Overview of Faults

The F317 fault is a major fault at the Jianshan underground mine in Panzhihua, China. Due to its unique geographical location, the F317 fault has a significant impact on surface rock movement during underground mining, so further research is required to determine the mode and magnitude of its impact to determine a safe and efficient mining solution. If the fault seriously affects the safety of the quarry and the stability of the surface road, backfilling, cable anchors, and grouting should be adopted immediately to stabilize the rock mass and reduce the risk of rock fall and ground collapse. The spatial location of the F317 fault with the orebody is shown in Figure 2.

![Figure 2. Map showing the location of the F317 fault in relation to the IV-VIII ore belt.](image2)
The main rock body of the F317 fault is iron-bearing gabbro and the tensile strength of the iron-bearing gabbro is 12.16 MPa, according to the onsite engineering geological investigation and indoor rock mechanics experiments; the rock quality grade is II, which can provide basic data for the subsequent numerical simulation study.

3. Fault Model
3.1. Numerical Simulation Models of Fault Surfaces

The F317 fault is inverse-translational. It is located 50–130 m west of Line 28 and extends north to Sulphur Gully. It is the largest group of north-south faults in the mine area and runs through the western end of the mine area, forming a natural boundary with the Daomakan Mine. All rock layers and northeast-trending reverse faults are misaligned. It extends 4500 m, with a fracture zone of 15–30 m, strike 0°, inclined east, dip 75°–86°. The fracture zone is composed of mylonite and crushed rock, with lamprophyre and cleavage development, obvious fault cliffs, structural masks and scrapes, and intrusion of late medium-acidic veins (plagioclase veins, orthoclase veins, and amphibolite veins). This group of faults is more destructive to the ore body and rock (body) layers in the ore zone.

The fault has no engineering control within the mine area and is poorly controlled, but surface indications are evident. The fault is close to the security pillar and the road and therefore has a greater impact on this study. Based on relevant information and survey data, a numerical simulation model of the F317 fault was established. The spatial location of this fault in relation to the highway is shown in Figure 3.

3.2. Fault Surface Slip Mechanics Model

Under normal conditions, faults tend to slip due to changes in positive and shear stresses on the fault surface, which in turn affects the stability of the fault surface; thus, it is essential to study the changes in stresses on the fault surface during the mining of the ore body [31,32]. In the study of the impact of stresses in the fault, the stresses considered are positive stresses, as well as shear stresses on the weak surface, of which positive stresses can be divided into horizontal and vertical stresses, so a section can be taken in the direction of the vertical fault and, according to the relationship between the stresses in the upper and foot plates of the fault, a triangular microelement of one unit thickness is taken for mechanical analysis, according to which the possible sliding displacement on the fault surface is analyzed; its mechanical model is shown in Figure 4.
3.2. Fault Surface Slip Mechanics Model

Under normal conditions, faults tend to slip due to changes in positive and shear stresses acting on the fault surface. As depicted in Figure 4, the forces in the parallel and perpendicular directions of the fault surface can be mechanically analyzed separately, with the X-direction being horizontal to the fault surface and the Y-direction being perpendicular to the fault surface; the corresponding mechanical relationships can be created as shown below [33].

\[
\begin{align*}
F_x &= (\tau + \sigma_v \cos \theta \sin \theta - \sigma_h \sin \theta \cos \theta) ds \\
F_y &= (\sigma + \sigma_v \cos \theta \sin \theta - \sigma_h \sin \theta \cos \theta) ds \\
\tau &\leq \sigma \tan \psi + c
\end{align*}
\]

where \(F_x\) is the force on the microelement in the X-direction, MPa; \(F_y\) is the force on the microelement in the Y-direction, MPa; \(\sigma_h\) is the horizontal stress, MPa; \(\sigma_v\) is the vertical stress, MPa; \(ds\) is the area of contact between the microelement and the fault surface; \(\psi\) is the angle of internal friction of the rock at the fault surface, \(^\circ\); \(c\) is the cohesion of the rock at the fault surface, MPa, and \(c\) is taken to be 0 because of the severe fragmentation of the rock at the fault surface.

Since the cohesion values on the fault face are very low, when subjected to stresses in the horizontal and vertical directions, the microelement does not undergo displacement in the vertical direction due to the blockage of the fault subduction and the microelement tends to undergo slip in the direction parallel to the fault face, which leads to the following equation.

\[
\tau = \sigma \tan \psi + c
\]

Using Equations (1) and (2), the equation for the force on the microelement in the X-direction can be found as:

\[
F_x = (\tau + \sigma_v \cos \theta \sin \theta - \sigma_h \sin \theta \cos \theta) ds \\
= (\sigma \tan \psi + c) ds + \sigma_v \cos \theta \sin \theta ds - \sigma_h \sin \theta \cos \theta ds \\
= \left[ (\sigma_v \cos^2 \theta + \sigma_h \sin^2 \theta) \tan \psi + c \right] ds + (\sigma_v \cos \theta \sin \theta - \sigma_h \sin \theta \cos \theta) ds
\]

The sliding of microelements can be divided into two cases: one is sliding downward along the fault surface and the other is sliding upward along the fault surface. From the above equation, it can be seen that when \(F_x > 0\), the microelements slide upward and both the hanging wall of the fault bulges upward relative to the footplate of the fault and the hanging wall of the fault sinks with a smaller displacement. When \(F_x < 0\), the microelements slide downward and both the hanging wall of the fault collapses downward relative to the footplate of the fault and the hanging wall of the fault sinks with a larger displacement, so the possible sliding of the fault can be judged by this equation.

From Equation (3), the magnitude of \(F_x\) is mainly related to the contact area \(ds\) between the microelement and the fault surface, the dip angle \(\theta\) of the fault, the internal friction angle \(\psi\) of the fault, and the cohesive force \(c\). The contact area \(ds\) between the microelement
and the fault is constantly greater than zero and the dip angle \( \theta \) of the fault, the internal friction angle \( \psi \) of the fault, and the cohesive force \( c \) is known, as long as the horizontal stress \( \sigma_h \) and the vertical stress \( \sigma_v \) can be obtained, the magnitude of \( F_x \) can be found.

As this study mainly considers the effect of the presence of the fault on the surface subsidence displacement when underground mining is carried out, the values of the dip angle \( \theta \), the internal friction angle \( \psi \), the cohesion \( c \), the horizontal stress \( \sigma_h \), and the vertical stress \( \sigma_v \) of the fault are taken at the outcrop of the fault. According to the engineering geological survey data and relevant rock mechanics tests, the dip angle of the Jianshan Iron Mine is 80°, the internal friction angle of the fault is 20°, the cohesion force is 0.018 MPa, the horizontal stress is 1.30 MPa, and the vertical stress is 0.083 MPa and \( F_x = -0.064 \) MPa at the surface fault outcrop can be calculated according to Equation (3). The underground mining is in the upper part of the fault, so it can be inferred that at the end of the underground mining, the subsidence displacement is mainly concentrated above the ground mining (on the upper side of the fault). The fault prevents the cave-in from propagating to the road (the foot side of the fault), which protects the road from cave-ins during the underground mining process and allows for appropriate adjustment of the mining area to achieve safe, efficient, and economic mining.

4. Model Building and Solution Design

4.1. Principle of the Contact Surface Method

Contact surface units in FLAC\(^3D\) consist of a series of three-node triangular units, where the contact surface unit distributes the triangular area into individual nodes, each of which has an associated representation area [34–37]. A quadrilateral area can be formed by any two triangular contact surface shapes; nodes are automatically generated at the vertices of the triangular contact surfaces and multiple quadrilateral-constituted faces are generated on top of this by generating contact units in this way, a diagram of the contact surface mechanism is shown in Figure 5. When the contact surface is in contact with other mesh surfaces, contact surface nodes are automatically generated as a means of achieving tension, slip, separation, and closure of different mesh groups on the specified surface and express this relationship through normal stiffness, shear stiffness, etc. The use of contact surfaces for modeling the slip process of faults is, therefore, a practical approach that provides a more reasonable representation of the fault damage mechanism.

![Contact surface mechanism diagram](image)

**Figure 5.** Contact surface mechanism diagram.

4.2. Numerical Calculation Modeling

Underground mining at the Jianshan Iron Mine uses sublevel drilling and stage drawing mining, with the first step being the mining room, followed by cemented infill,
and the second step being the mining pillar, followed by waste rock backfill. Without compromising the scientific validity of the simulation, the mining steps are appropriately simplified, with one-step-back mining and filling at the same time and two-steps-back mining and filling at the same time in different pan areas at the same stage so that the calculation results should be more dangerous compared with the actual situation and the simulation results will be more conservative, which can guarantee the safety and reliability of the production process. For the different stages of mining, underground mining uses a downward mining sequence, both mining the 1160 m stage first and then the 1094 m stage.

The numerical simulation model was established using Midas GTS/NX. This simulation focuses on the impact of the presence of faults on surface collapse during mining in two stages, 1160 m and 1094 m below the isolated pillar, where the underground mining process has a width of 20 m and a length of 100 m for the mine house and a width of 20 m and a length of 100 m for the pillar, with the mine house first and then the pillar, and a stage height of 50 m. In order to simplify the calculation, the ore body model and surface model were established and based on St. Venant’s principle, 3~5 times the radius of the area of interest was selected as the model boundary, and the final calculation model was established [38]. The model size is $4300 \times 3775 \times 1593$ (length $\times$ width $\times$ height), the model is divided into 1,265,121 calculation units, and the numerical calculation model is shown in Figure 6a.

Figure 6. Numerical calculation model: (a) surface and ore body model; (b) location of monitoring points.

In order to analyze the impact of the F317 fault on the west side of the road during the underground mining of The Jianshan underground mine in Panzhihua Iron Mine, monitoring points were set up at the corresponding road safety protection zone (20 m outside the road) for the more dangerous locations in the road and the inflexion points near the mining site, in order to obtain the displacement and stress changes at the location of the key monitoring points in the road safety protection zone during the mining process and to make a judgement on the safety of the road on this basis. Figure 6b shows the location of the monitoring points for the road safety protection zone (Figure F317 fault thickness is 0 and the road line is taken as the outer contour of the road near the quarry side), where
white marks the surface road, yellow marks the road safety protection zone, black marks the F317 fault, and the five-pointed stars are the locations of the monitoring points (where 30 key point locations were selected for key monitoring studies and numbered 1–30).

4.3. Determination of Calculation Parameters

Rock core samples involving the relevant study area were taken according to the onsite engineering geological survey, the size and quantity of rock samples were determined according to the Standard for Engineering Rock Test Methods (GB/T50266-2013) [39], and the rock blocks were processed. The MTS 815 testing machine of Central South University was then used to carry out indoor rock mechanics experiments and rock mechanics parameters such as uniaxial compressive strength and tensile strength of the rock samples were obtained after uniaxial tensile, triaxial tensile, and Brazilian splitting experiments, which laid a solid foundation for the accuracy of the numerical simulation calculation results. As rock mass parameters and rock parameters still need to be converted, the corresponding rock strengths were obtained by discounting based on the Hoek–Brown criterion [40] to obtain the rock mechanical parameters required for this numerical simulation; the specific parameter results are shown in Table 1.

Table 1. Physical and mechanical parameters of the rock mass.

<table>
<thead>
<tr>
<th>Mechanical Indicators</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe1</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>1.214</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>3.786</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.270</td>
</tr>
<tr>
<td>Angle of internal friction (°)</td>
<td>34.260</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>4.420</td>
</tr>
<tr>
<td>Bulk modulus (GPa)</td>
<td>2.743</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>1.491</td>
</tr>
<tr>
<td>Internal Cohesion (MPa)</td>
<td>2.275</td>
</tr>
</tbody>
</table>

For the simulation of models with contact surfaces, the parameters of the contact surfaces are also determined. The normal stiffness $K_n$ and shear stiffness $K_s$ are calculated as ten times the equivalent stiffness of the hardest surrounding area; the tensile strength is set to 0 due to partial fragmentation of the fault face, where the normal and shear stiffnesses are calculated as follows:

$$
K_n = K_s = 10\max \left[ \frac{(K + \frac{4}{3}G)}{\Delta Z_{\min}} \right]
$$

(4)

where $K$ is the bulk modulus, GPa;
$G$ is the shear modulus, GPa;
$\Delta Z_{\min}$ is the minimum size of the connection area in the normal direction of the contact surface, m.

5. Analysis of Simulation Results

During the process of the deep ore body and security pillar recovery at the Jianshan Iron Mine, there are two main factors affecting road safety. On the one hand, the maximum tensile stress in the road protection zone does not exceed the ultimate tensile strength of the rock body to occur tensile damage. On the other hand, the maximum sinking displacement of the road protection zone does not exceed the permissible range (<20 mm), leading to the collapse of the rock body [41]. Therefore, in this paper, the maximum tensile stress and maximum subsidence displacement of the road protection zone are selected as indicators to analyze the stability of the road in the presence and absence of the F317 fault.
5.1. Maximum Tensile Stress at Road Protection Zone

Figure 7 shows the maximum principal stress clouds for the two scenarios with and without the F317 fault. Due to a large number of simulation steps (mainly including the downward two stages of mining the ore house pillars), the results of each step are not shown and only the clouds atlas of tensile stress at the road protection zone after the second stage (1094 m stage) of mining the infill are taken for presentation. As shown in Figure 7a,b, when there is a fault, the tensile stress is concentrated at the bottom of the open pit and on both sides of the fault, no tensile stress appears at the road protection zone, and the maximum tensile stress is 2.21 MPa, which does not exceed the rock tensile stress. The tensile stresses are concentrated at the bottom of the open pit when there is no fault, and no tensile stresses occur at the road protection zone, where the maximum tensile stress is 2.19 MPa, which does not exceed the rock tensile stress. Both options approach the tensile strength of the rock mass and are prone to tensile damage at the base of the open pit and at the side slopes. Figure 7c,d show that, when there is a fault, the tensile stress is concentrated at the top and bottom of the quarry, with a maximum tensile stress of 1.82 MPa, which does not exceed the tensile stress in the rock, probably due to the fact that the ore body is mined on the hanging wall of the fault and the hanging wall has a tendency to deviate along the fault side towards the empty area of the quarry, but the tensile and extrusion of the rock occurs due to the obstructive effect of the footwall of the fault so that the area of tensile stress concentration on the hanging wall of the fault is greater. The tensile stress cloud shows that the road is stable under both scenarios, but the quarry is less stable due to the presence of faults.

Figure 7. Cloud atlas of tensile stress: (a) cloud atlas of tensile stress at road protection zone without the F317 fault; (b) cloud atlas of tensile stress at road protection zone with the F317 fault; (c) profile of tensile stress at road protection zone without the F317 fault; (d) profile of tensile stress at road protection zone with the F317 fault.

5.2. Subsidence Displacement at the Road Protection Zone

The sequence of steps in the simulation program began with the excavation of the mine room, followed by filling the body with a ratio of 1:4 for cementation filling. The second step was the excavation of the pillar, followed by backfilling with waste rock. The sinking displacement at the road protection zone was at its maximum at step 8 (pillar filling at the 1094 m stage) and therefore, due to space limitations, the results of the remaining steps are...
not presented in full. Figure 8 shows the distribution of Z-directional displacement at the road protection zone during step 8 of the 1094 m stage (pillar filling at the 1094 m stage). From Figure 8a, it can be seen that the subsidence displacement is mainly concentrated at the side slopes of the open pit. The maximum value of subsidence displacement at the road protection zone on the west side is 30.59 mm, which is greater than the safety limit value of 20 mm and is prone to cave-in and other accidents. Figure 8b shows that the subsidence displacement is mainly concentrated at the side slope of the open pit on the side of the F317 fault; the maximum value of subsidence displacement of the road protection zone on the west side is 16.92 mm, which does not exceed the safety limit value of 20 mm and is in a stable state. Figure 8c,d are positive profiles of the maximum sinking displacement of the road protection zone on the west side; the maximum sinking displacement is located in the middle of the top of the quarry. In comparison, it can be seen that, when the F317 fault is present, the sinking displacement on the fault side near the quarry is larger, while the sinking displacement on the roadside is smaller than when there is no fault, so the F317 fault effectively prevents the transfer of the mining area displacement to the road.

![Zone Z Displacement](image)

**Figure 8.** Cloud atlas of Z-directional displacements: (a) cloud atlas of Z-directional displacements at road protection zone without the F317 fault; (b) cloud atlas of Z-directional displacements at road protection zone with the F317 fault; (c) profile of Z-directional displacements at road protection zone without the F317 fault; (d) profile of Z-directional displacements at road protection zone with the F317 fault.

Statistical processing of the data from the 30 monitoring points set up in the road protection zone leads to a map of the subsidence displacement at the road protection zone with the mining steps, as shown in Figure 9. Regardless of the presence or absence of the F317 fault, the subsidence displacement of the monitoring points at the highway protection zone shows a trend of increasing and then decreasing from north to south, with the maximum settlement displacement point occurring in the area of the 80 m monitoring point (monitoring point 7). The overall curve is regular in an inverted “U” shape. In the absence of the F317 fault, the maximum subsidence displacement at the road protection zone increases gradually with the number of mining steps, with a sharp increase at step 3 (pillar mining at the 1160 m stage) and step 7 (pillar mining at the 1094 m stage). Because the ore houses on both sides of the pillar have been mined and filled, but the tensile strength...
and compressive strength of the filling body are smaller than the ore body, the filling body is squeezed and deformed by surrounding rock and the surface subsidence displacement changes greatly. Therefore, this is the most dangerous stage. Because of strengthening the layout of mining area safety control measures, monitoring whether the displacement and stress changes near the fault are abnormal will establish corresponding early warning and forecasting systems. The maximum value of sinking displacement was 30.59 mm at step 8 (pillar filling at the 1094 m stage), which exceeded the 20 mm safety threshold value. In the presence of the F317 fault, the maximum subsidence displacement at the road protection zone increases more slowly with the number of mining steps than in the absence of the F317 fault and is greater in the first two mining steps (room mining and filling at the 1160 m stage) than in the absence of the F317 fault. The maximum subsidence displacement was 6.3 mm but did not exceed the 20 mm safety threshold value, probably due to the presence of the F317 fault, which disturbed the highway stability during the first stage of mining and thus caused the greater collapse. The maximum sinking displacement value was 16.92 mm at step 8 (pillar filling at the 1094 m stage), which did not exceed the 20 mm safety threshold value.

The maximum Z-directional displacement of the road protection zone on the west side is 19.63 mm, which does not exceed the 20 mm safety threshold value. In Figure 9a, the side slope of the open pit near the side of the F317 fault is the greatest at step 8 (pillar filling at the 1094 m stage), so the Z-directional displacement at the road protection zone during step 8 of stage 1094 m (pillar filling at the 1094 m stage) is mainly concentrated at the side slope of the open pit and the quarry near the road, where the X-directional displacement is located at the side slope of the open pit near the side of the F317 fault and the direction is moving to the east. The maximum X-directional displacement of the road protection zone on the west side is 42.17 mm, which is greater than the safety limit value of 20 mm and is prone to collapse and other accidents. Figure 9b shows that the X-directional displacement when there is no F317 fault is mainly concentrated at the side slope of the open pit on the side of the F317 fault. The maximum X-directional displacement of the road protection zone on the west side, the maximum X-directional displacement is located at the side slope of the open pit and the quarry near the road, where the X-directional displacement at the surface road is positive, i.e., there is a tendency to move in the east direction, and the X-directional displacement at the quarry is negative, i.e., there is a tendency to move in the west direction. The quarry side of the F317 fault near the surface is, therefore, susceptible to sliding damage, and the quarry side of the quarry near the road

Figure 9. Z-directional displacement of monitoring points at the road protection zone: (a) without the F317 fault; (b) with the F317 fault.

Figure 10 shows a cloud plot of the distribution of X-directional displacements at the road protection zone during step 8 of stage 1094 m (pillar filling at the 1094 m stage), where X positive is the direction due east of the model and X negative is the direction due west of the model. From Figure 10a, it can be seen that the X-directional displacement when there is no F317 fault is mainly concentrated at the side slope of the open pit near the side of the F317 fault and the direction is moving to the east. The maximum X-directional displacement of the road protection zone on the west side is 19.63 mm, which does not exceed the safety limit value of 20 mm and is in a stable state. From Figure 10b,d, which both show the X-directional displacement at the maximum value of the road protection zone on the west side, the maximum X-directional displacement is located at the side slope of the open pit and the quarry near the road, where the X-directional displacement at the surface road is positive, i.e., there is a tendency to move in the east direction, and the X-directional displacement at the quarry is negative, i.e., there is a tendency to move in the west direction. The quarry side of the F317 fault near the surface is, therefore, susceptible to sliding damage, and the quarry side of the quarry near the road...
is less stable in terms of perimeter rock. It is clear from the figure that when the F317 fault is present, the X-directional displacement on the side of the fault near the quarry is greater than the X-directional displacement on the roadside of the fault, so the presence of the F317 fault can effectively prevent the road from sliding towards the open pit side.

Statistical analysis of the data from the 30 monitoring points at the road protection zone gives a graph of the X-directional displacement at the road protection zone with the mining step, as shown in Figure 11, where the X-positive direction is due east. As can be seen from Figure 11, regardless of the presence of the F317 fault, the X-directional displacement increases with the increase of the excavation step and the direction is due east, i.e., there is a tendency to slip to the side of the open pit, while the X-directional displacement is more significant at the 106 m monitoring point (monitoring point 8) and 247 m monitoring point (monitoring point 16) and the overall curve shows an inverted “W” shape. In the absence of a fault, the X-directional displacement changes dramatically at step 3 (pillar mining at the 1160 m stage) and step 7 (pillar mining at the 1094 m stage) and starts at step 3 (pillar mining at the 1160 m stage) with all locations north of the road protection zone monitoring point 18 having X-directional displacements greater than the safety boundary value of 20 mm. By step 8 (pillar filling at the 1094 m stage) with all locations north of the road protection zone monitoring point 26 having X-directional displacements greater than the safety boundary value of 20 mm, the majority of the kilometer locations are in a dangerous condition with a high probability of slippage to the side of the open pit. In the presence of the F317 fault, the X-directional displacement varies considerably at step 3 (pillar mining at the 1160 m stage) and at step 8 (pillar filling at the 1094 m stage), the maximum X-directional displacement at monitoring point 8 is 19.63 mm, which does not exceed the safety limit of 20 mm and is less than the displacement value in the absence of the F317 fault.

Figure 10. Cloud atlas of X-directional displacements: (a) cloud atlas of X-directional displacements at road protection zone without the F317 fault; (b) cloud atlas of X-directional displacements at road protection zone with the F317 fault; (c) profile of X-directional displacements at road protection zone without the F317 fault; (d) profile of X-directional displacements at road protection zone with the F317 fault.
The Y-directional displacement at the road protection zone is at its maximum at step 8 (pillar filling at the 1094 m stage). Therefore, the stability analysis focuses on the Y-directional displacement at this stage. Figure 12 shows a cloud of the distribution of the Y-directional displacement at the road protection zone during step 8 of stage 1094 m (pillar filling at the 1094 m stage), where the positive Y-directional displacement is in the due south direction and the negative displacement is in the expected north direction. From Figure 12a, it can be seen that the Y-directional displacement is mainly concentrated at the north of the road and the slope of the open pit, the maximum Y-directional displacement of the road protection zone is 19.25 mm, which is within the safety limit of 20 mm, and the road is in a relatively safe condition. Figure 12b shows that the Y-directional displacement is significantly more concentrated on the side of the F317 fault near the open pit and the maximum Y-directional displacement at the road protection zone is 3.05 mm, which does not exceed the safety limit of 20 mm and is in a stable state. From Figure 12c,d, which both show the positive profile taken from the west side of the road at the nearest point to the quarry, the Y-directional displacement at the open pit is a positive displacement, regardless of the presence of the F317 fault, and there is a significant reduction at fault. The Y-directional displacement of the quarry is negative and the fault slows down the displacement transfer, which strengthens the surrounding rock’s stability.

Statistical analysis of the data from the 30 monitoring points at the road protection zone gives a Y-directional displacement map at the road protection zone with the mining step, as shown in Figure 13. The Y-direction is due south, regardless of the existence of the F317 fault, the Y-direction displacement is less than the safety boundary value of 20 mm, the Y-directional displacement of the monitoring points on the north side of the road is larger than the Y-directional displacement of the monitoring points on the south side of the road, among which the Y-direction displacement of the monitoring points north of the 365 m monitoring point (monitoring point 19) are all harmful, i.e., there is a tendency to move to the north, and the Y-direction displacement of the monitoring points south of the 365 m monitoring point (monitoring point 19) are all positive, i.e., there is a tendency to move to the south, tensile damage may occur at the 365 m monitoring point (monitoring point 19) road protection zone, which needs to be monitored. In the absence of faulting, step 8 (pillar filling at the 1094 m stage) has the most significant Y-directional displacement values, with the most considerable positive value located at monitoring point 371 m (monitoring point 26) with a maximum value of 3.68 mm and the most significant negative value located at monitoring point 0 m (monitoring point 1) with a maximum value of $-19.75$ mm. In the presence of a fault, the maximum positive value is at monitoring point 371 m (monitoring point 26) at step 4 (pillar filling at the 1160 m stage) with a maximum value of 2.95 mm and the maximum negative value is at monitoring point 0 m (monitoring point 1) at step 2.
(room-filling at the 1160 m stage) with a maximum value of −3.35 mm, changing more slowly than in the absence of a fault.

**Zone Y Displacement**

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**Figure 12.** Cloud atlas of Y-directional displacements: (a) cloud atlas of Y-directional displacements at road protection zone without the F317 fault; (b) cloud atlas of Y-directional displacements at road protection zone with the F317 fault; (c) profile of Y-directional displacements at road protection zone without the F317 fault; (d) profile of Y-directional displacements at road protection zone with the F317 fault.

**Figure 13.** Y-directional displacement of monitoring points at the road protection zone: (a) without the F317 fault; (b) with the F317 fault.

### 5.3. F317 Fault Simulation Results and Status Validation

During the practical investigation of damage to surface roads, open pit slopes, and buildings at the Jianshan Iron Mine, it was found that slight slippage had occurred between the outcrop of the F317 fault and the upper open pit slope of the quarry, i.e., part of the hanging wall of the F317 fault (near the quarry side) had sunk under the influence of mining, affecting the stability of the open pit slope. However, the slip did not show a
tendency to propagate towards the highway on the west side and the surface and buildings attached to the protective zone of the highway on the west side were not damaged and were in a safe condition. The spatial location relationship between the F317 fault and the road and the slope subsidence of the open pit can be clearly found by using DJI UAV to photograph the situation at the Jianshan Iron Mine, as shown in Figure 14.

As can be seen from Figure 14a, the underground mining area is located below the location of the road on the west side, so, during the subsequent underground excavation, there will be a large area of overhang in the underground mining site on the west side, which will definitely cause the surface of the ground to collapse within a particular area. According to the numerical simulation results, it can be seen that the area affected by mining includes the road on the west side and the road on the west side is prone to shear break collapse. However, the F317 fault exists between the quarry and the road. As the fault is a weak surface, shear damage occurs first during the mining process, resulting in the early release of some of the shear stress on the west side, relieving the stress concentration caused by mining. As shown in Figure 14b, partial slip damage has now occurred on the F317 fault while satisfying the numerical simulation results, such as more significant subsidence displacement on the upper side of the F317 fault (near the quarry side) and possibly dangerous situations such as collapse, and relative slip has occurred at the F317 fault. The F317 fault disrupts the continuity of the mountain but at the same time isolates the transmission of mining effects, thus allowing the stability and integrity of the mountain on the west side to be protected and the surface road to be in a safe condition without the need for road relocation. Scientific reference for the analysis of road stability during the recovery of mining pillars at the Jianshan Iron Mine uses the contact surface method in FLAC$^{3D}$ to simulate the F317 fault.

6. Conclusions

Research on fault-induced ground movement during mining has mainly focused on mechanical theory calculations, but, due to the complexity of faults and their unpredictability and other characteristics, they may cause great trouble to mine production. Therefore, this paper proposes to use the contact surface calculation in Flac3D to simulate the actual environment of faults, consider the rock movement of faults due to mining in three-dimensional space, and analyze and predict the impact that the F317 fault will have on the surface road in the future deep ore body mining process in conjunction with the actual production of the Jianshan underground mine in Panzhihua Iron Mine. The main findings of the study are as follows:

(1) By establishing a fault-slip mechanics model through theoretical analysis, it can be analyzed that the fault-slip situation is mainly related to the magnitude of the positive and shear stresses. Calculations based on the relevant parameters at the Jianshan Iron Mine show that, during the underground mining process, the area above the ground...
mining (hanging wall of the F317 fault) slides along the fault surface relative to the road-side (footwall of the F317 fault), effectively preventing the propagation of the subsidence displacement caused by the ground mining to the road.

(2) Regardless of the presence of the F317 fault, there is no tensile stress distribution at the road protection zone and the maximum tensile stress in the quarry area does not exceed the corresponding tensile strength of the rock mass. When there is the F317 fault, the stretching and squeezing of the rock around the quarry are more pronounced and the peak of the maximum tensile stress is located at the top and bottom of the quarry. The stress monitoring in this area should be strengthened during the recovery process.

(3) The presence of the F317 fault effectively prevents the propagation of subsidence displacement to the west side of the road during underground mining. In the absence of the F317 fault during the simulation, the maximum subsidence displacement at the road protection zone is 30.59 mm, which exceeds the safety limit by 20 mm and makes the road vulnerable to collapse. With the F317 fault during the simulation, the maximum subsidence displacement at the road protection zone is 16.92 mm, which is within the safety limit value. Additionally, because of the presence of the F317 fault, the upper part of the quarry (hanging wall of the fault) has more significant subsidence displacement than the road protection zone (footwall of the fault) and should be monitored for critical locations.

(4) The presence of the F317 fault effectively prevents the road from sliding to the side of the open pit. In the absence of the F317 fault during the simulation, the maximum X-directional displacement at the road protection zone is 42.17 mm, which exceeds the safety limit by 20 mm and makes the road susceptible to slippage. The maximum X-directional displacement at the road protection zone with the F317 fault during the simulation is 19.63 mm, which is within the safety limit value.

(5) The maximum Y-directional displacement at the road protection zone was within the safety limits during the simulation, regardless of the presence or absence of the F317 fault. The maximum Y-directional displacement at the road protection zone is 19.75 mm in the absence of the F317 fault during the simulation. The maximum Y-directional displacement at the road protection zone is 3.35 mm when the F317 fault is present during the simulation.

(6) The numerical simulation results predicted that the upper plate of the F317 fault (near the quarry side) would undergo subsidence slip. The actual investigation site found that landslides occurred at some locations between the F317 fault and the side slopes of the open pit. The numerical simulation results are consistent with the theoretical calculations and the actual situation, and the simulation results can guide mine production.

The research method of this paper is mainly through a combination of theoretical research and numerical simulation to mutually verify the existence of the F317 fault that can effectively avoid the propagation of subsidence displacement to the road caused by deep ore body mining, which provides reference information for the actual production of the Jianshan underground mine and can help the mine to improve the resource recovery and also lay a solid foundation for the design of future monitoring programs. However, as the underground mining of the Jianshan underground mine is still in its preliminary stage, the mining depth is not yet deep enough and the relevant monitoring system is not yet perfect, so the actual stress and displacement changes of the fault subjected to mining movement are not yet available; therefore, I will continue to keep an eye on the production of the mine and plan to improve my research when the time is right.


All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Key Research and Development Program of China (Grant No. 2020YFC1909801).
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


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