Research Article

Geological Survey and Comprehensive Analysis of a Dangerous Slope in the Weibei Limestone Mine

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There are abundant limestone resources in Weibei area. However, under the influence of a complex geological environment and harsh external environment, they often suffer from various types of serious geological disasters, which seriously threaten the safety of the people in the mining area and the development of mining resources. Therefore, it is urgent to carry out relevant governance. Firstly, combined with the field engineering geological data of a typical limestone quarry slope in Weibei, this paper makes a detailed geological survey of the study area. Then, the geometric model of the limestone mine slope is established to analyze the stress relationship between each block and its failure mode. Finally, a deep Newtonian force monitoring and early-warning system is set up in the dangerous area of large deformation of the slope to carry out the early warning treatment of reinforcement. The results show that (1) limestone is the main component of the mine, followed by mudstone, with developed joints and fissures, broken rock mass, and high hidden danger of engineering geological disasters; (2) in addition to bending and toppling failure on the surface of the mine slope, there are three failure modes: toppling failure along the joint surface, combined failure along the joint and plane, and failure along the outward structural plane; and (3) the NPR anchor cable is used to strengthen the slope, and the real-time monitoring of the slope force changes is realized, which has a particular reference significance for the study of similar significant deformation failure mechanisms of the slope and imminent slide warning.

1. Introduction

The Weibei area between the Guanzhong Plain and the Loess Plateau is the richest area in Shaanxi Province in terms of limestone reserves and production, and is an important part of cement and other building materials. The restoration of high and steep rock surfaces in limestone mining areas has always been difficult to restore and treat the mine geological environment. In addition, due to the exceptional natural conditions of water shortage in Weibei area, the restoration and treatment of limestone mining areas are more complicated. After the founding of New China, systematic research on slope engineering began in China. Especially in recent years, the state has strengthened the attention to the mining area construction. Still, the lack of long-term mining geological environment monitoring and governance, the safety of the people in the mining area, and the development of mining resources have produced a severe threat [1–9]. Therefore, to fully implement the spirit of the 19th National Congress of the Communist Party of China, it is necessary to explore a path of comprehensive management of sustainable mine geological environment management. It is essential to carry out a unique survey on the geological environment of Weibei limestone mines and conduct research on the prevention and control of geological disasters in the limestone mining area and the restoration and treatment of high and steep rock face open-pit mining.

The analysis method for slope stability is an important research object for studying slope-related issues [10–15], and slope calculation is one of the professional geotechnical engineering disciplines and its important branch [16, 17]. In recent years, experts and scholars have made many new and substantial progress in the field of research. Zhao et al. [18] opened up a new path for the stability analysis of the jointed
on-site and technical support will be provided for later restoration and treatment.

2. Analysis of Geological Conditions of the Weibei Limestone Mine

Baoji city and Xianyang city are rich in limestone in the Weibei area. Baoji is located in the west of Guanzhong, Shaanxi province, with 18172 km² and rich mineral resources. The Lian-Huo Expressway (G30), National Highway 310 (G310), and Longhai Railway pass through the area from east to west. The Baozhong Railway, Baocheng Railway, and the section from Baoji to Longxian of Baoshan Expressway have been completed and opened to traffic, running from north to south, connecting with neighboring provinces and cities. Within the scope of the city, county roads and village roads in all counties are developed and the transportation is extremely convenient. Another city rich in coal and limestone resources is Xianyang. The Xianyang International Airport has always been regarded as one of the largest airports in inland China. It is only 9 km away from the city and has an annual passenger flow of more than 6.4 million people. It can be seen that the Weibei area has a three-dimensional transportation network system extending in all directions and the railway, highway, and airport transportation are very convenient (Figure 1).

The central geomorphic unit of the Weibei area is the first-class loess tableland, which has a high altitude of 800–1500 m and a general trend of a sloping terrain from northwest to southeast. The loess hills are earth rock hills, a thin layer of loess covers the top of the slope, and the hill’s bedrock is exposed. The limestone mining area in the Weibei area mainly involves Cambrian, Ordovician, and Carboniferous strata, and Quaternary strata are exposed on the surface (Figure 1).

3. On-Site Engineering Geological Survey and Failure Mode Analysis

3.1. On-Site Engineering Geological Survey. The geological survey method adopted in this paper is the line survey method, which is a common method in geology at home and abroad. The basic method is to lay out one or more lines intersecting at any angle or parallel to each other in the rock outcrop and record in detail the joint occurrence, number of lines, trace length, and other parameters intersecting with these lines. In order to ensure the objectivity of the data, the same points were repeatedly sampled and recorded. The detailed investigation area of the stope slope in the Weibei limestone mine includes the first step of the main stope, the second step of the main stope, the south stope, and the north stope. The survey line method is used to select a section with good outcrops on the steps, a flat ground, and a walking survey record condition to lay out a detailed survey line. On each survey line, several survey points, boundary points, water outlet points, and rock vein points are recorded according to the length of the steps. They are set along the slope direction, and the length varies, about...
5 m–50 m. In this paper, the density of joints is obtained by counting the number of joints per unit length. According to the above principles, a total of 4 detailed survey lines were laid in the limestone mine open-pit slope, represented by English letters J, D, V, and C (Figure 2) and 22 lithologic demarcation points or fracture zones and two water outlet points were recorded and catalogued.

3.2. Field Engineering Geology Investigation and Description of the Quarry

3.2.1. First Step Slope of the Main Quarry. The survey length of the slope platform is about 103 m, and the width of the steps is about 11 m. It is located north of the main stope, and the platform is east-west with a slope angle of about 73°. A total of 8 measurement points were recorded for the first step (Figure 3). The slope type of the platform is a rocky antidip slope. The slope rock mass is mainly limestone, followed by mudstone. The foot of the slope is an accumulation of limestone mining debris, and the slope on the east side of the step is mainly covered by the accumulation of gravel and the overburden of mine restoration treatment. The distribution density of joint fissures \( f = 1–4 \) strips/m.

The main features of each point on the first step of the main quarry are as shown in Figure 4. The joint and fissure distribution density at point D1 is \( f = 1–2 \) bars/m. The outcrop rock mass at point D2 is relatively complete, three sets of joints are measured, and two weak mudstone interbeds are exposed. The gravel at point D3 is accumulated chiefly at the toe of the slope. Three sets of joints are measured, one of which penetrates through the cracks up and down, and the widest part of the crack is 20 cm. The fillings are mainly calcite crystals and soil. Measure two sets of joints at point D4, and there is a water outlet nearby. Small rock fragments at point D6 are accumulated at the foot of the slope, and the surface of the rock mass shows traces of historical drilling and blasting. The outcrop rock mass at point D7 is relatively broken, and limestone fragments accumulate at the slope’s foot. Three sets of joints are measured, a layer of weak mudstone interlayer is exposed, and a layer of soil is attached to the rock’s surface on the left side of the measurement point. The outcrop rock mass at end D8 is relatively broken, and two sets of joints are measured, and there is no sizeable intact rock mass.

3.2.2. Second Step Slope of Main Quarry. The survey length of the slope platform is 153 m, located north of the excavation area of the main stope. The platform is east-west, and the slope angle is about 78°. The features of the platform are shown in Figure 5. A total of 14 measurement points were recorded for the second step, and the slope type was a rocky steep-dip antidip slope. The composition of the slope...
rock mass is mainly limestone, occasionally mudstone—the distribution density of joint fissures \( f = 1–4 \) strips/m.

This survey line starts from the second step, 2 m, and surveys eastward along the road. The main features of the slope point of the second step of the main quarry are shown in Figure 6. Two sets of joints are measured at point J1, and the distribution density of joint fissures is \( f = 1–2 \) joints/m. Two groups of joints were measured at point J2 and overlaid with thick miscellaneous soil. The outcrop rock mass at point J3 is relatively broken, and four groups of joints are measured. Many small limestone fragments are accumulated at the foot of the slope. There is a layer of a broken argillaceous limestone interlayer at J4, about 20 cm thick. Two long cracks are found in the J5 point. Four groups of joints were measured at point J6, and the outcrop rock mass was relatively complete, with the soil stripped by weathering on the surface. The surface of the rock strata at J7 is interlaced with gray and red, and the surface sediments are denuded by weathering. Three joints were measured at the J8 point, accompanied by a calcite crystal and mudstone interlayer with a width of about 10 cm. There is an interlayer with calcite as the main filler near J9. Some falling gravel accompanies the foot of the slope at point J10. A horizontally extending calcite interlayer appears at point J11. There are two apparent traces of drilling and blasting left by history at point J12. The outcrop rock mass at point J13 is relatively complete, and the surface shows five traces of historical drilling and blasting. The outcrop rock mass at end J14 is somewhat broken, the surface is severely weathered, as well as the overlying thin soil layer.

Figure 3: The characteristics of the first step stope and the arrangement of the points.

Figure 4: Main features of each point on the first step of the main quarry. (a) Mudstone interlayer. (b) Folds. (c) Multiple sets of mudstone interbeds. (d) Exposed weathered rock mass.
3.2.3. South Quarry. The survey length of the slope platform is about 110 m, and it is located south of the main stope excavation area. The platform has a C-shaped trend and a slope angle of about 75°. A total of 8 measuring points were recorded in the south stope. The slope rock mass is mainly limestone, occasionally mudstone. The rock mass on the east side of the entire stope is broken, dominated by limestone (Figure 7). The distribution density of joint fissures $f = 1-4$ strips/m.

The main characteristics of the survey points on the slope of the south stope are shown in Figure 8. The outcrop rock mass at point C1 is relatively complete, with three mudstone interlayers exposed, penetrating right and left, and the distribution density of joints and fissures $f = 1-2$/m. There is

Figure 5: The characteristics of the second step stope and the arrangement of the points.

Figure 6: Main features of each point on the second step of the main quarry. (a) Rock fragmentation. (b) Argillaceous limestone interbed. (c) Cracks through up and down. (d) Long joint. (e) Calcite crystal, mudstone interlayer. (f) Drilling and blasting marks.
a minor horizontal interbedded mudstone exposed at point C2, and there is a gravel deposit on the right side of the measuring point. The outcrop rock mass at point C3 is relatively broken, the distribution density of joints and cracks is \( f = 2-3 \) pieces/m, and the shots are pretty developed. Noticeable wrinkles appear at point C4. The rock at point C5 is broken, trials are developed, and there is a fan-shaped gravel deposit. The outcrop rock mass at point C6 is complete, and two groups of joints are measured. The distribution density of joint fissures is \( f = 1-2/m \). The whole rock mass at C7 is

Figure 7: The characteristics of the south quarry and the arrangement of the points.

Figure 8: Main features of each point on the south quarry. (a) Folds. (b) Rock fragmentation. (c) Fan-shaped gravel stack. (d) Joint development.
complete. The rock mass at point C8 is broken and has many cracks.

3.2.4. North Quarry. The survey length of the slope platform is about 105 m, and the step width is about 15 m. It is located in the northernmost part of the excavation area of the main stope. The platform has a U-shaped trend with a slope angle of about 70°. The platform’s characteristics are shown in Figure 9. Six measurement points were recorded in the north slope, and the slope type is a rocky bedding slope. The composition of the slope rock mass is mainly limestone, occasionally mudstone.

The main features of the survey points on the slope of the north stope are shown in Figure 10. Two joints are measured at point V1, and one layer of the weak mudstone interlayer is exposed. The distribution density of joint fissures $f = 1-2/m$. Four sets of joints are measured at the V2 point, with broken rocks and developed fissures. At point V3, the stone is broken and large cracks appear locally. Two groups of joints were measured at the V4 point. The outcrop rock mass was broken, the rock strata were vertical, and anticlinal folds were exposed. Three layers of weak mudstone interlayers are exposed at V5, and the distribution density of joints and fractures is $f = 1-3/m$. The rocks at point V6 are

Figure 9: The characteristics of the north quarry and the arrangement of the points.

Figure 10: Main features of each point on the north quarry. (a) Folds. (b) Cracks developed. (c) Rock crushing. (d) Fracture.
broken, and the crushed stones are piled up at the foot of the slope.

3.2.5. Rock Integrity Zoning. The most basic attribute that affects the stability of engineering rock mass is the basic quality of rock mass, which is inherent in rock mass. The basic quality of rock mass depends on the internal factors that constitute the structural characteristics of rock mass, and the integrity of rock mass is one of the controlling factors. Based on the field investigation of each step in the four areas of J, D, C, and V, and according to the zoning standards in Table 1, the integrity qualitative description and zoning of area J and area D with a large rock mass area in the exposed slope of the stope are mainly carried out. The final zoning is shown in Figure 11.

(1) Complete Partition (A)
According to the qualitative classification standard in Table 1 and the field investigation results, the "complete partition" of slope rock mass in J and D areas is mainly concentrated in the upper left part and the lower right portion of the J investigation area and there are fewer intact rock masses in general.

(2) Relatively Complete Partition (B)
According to the qualitative classification standard in Table 1 and the field investigation results, the exposed rock mass of the slope in areas J and D is generally a relatively complete area with a thickly layered structure and pleasing combination.

(3) Relatively Broken Partition (C)
According to the qualitative classification standard in Table 1 and the field investigation results, very few rock masses in J and D survey areas are in a layered structure and relatively broken state. The rock mass structure in this area is mainly a fracture block structure, and the number of joint sets is more than 3. It is primarily distributed at the edge of the exposed surface of the slope, and the detailed distribution is shown in Figure 11. The areas marked with yellow are relatively broken.

(4) Extremely Broken Partition (D)
The extreme fracture zone is distributed at the bottom of the whole rock slope in zone J, which artificially controls the overburden and rock debris accumulation body. There is also rock debris accumulation in the step area of the hill between zone D and zone J, and the rock

<table>
<thead>
<tr>
<th>Completeness</th>
<th>Development degree of the structural plane</th>
<th>Degree of combination of main structural surfaces</th>
<th>Corresponding structure type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete</td>
<td>1–2</td>
<td>&gt;1.0</td>
<td>Good combination</td>
</tr>
<tr>
<td>Relatively complete</td>
<td>2–3</td>
<td>1.0–0.4</td>
<td>Combined with general</td>
</tr>
<tr>
<td>Relatively broken</td>
<td>≥3</td>
<td>0.4–0.2</td>
<td>Good combination</td>
</tr>
<tr>
<td>Fracture</td>
<td>≥3</td>
<td>≤0.2</td>
<td>Combined with general</td>
</tr>
<tr>
<td>Extremely broken</td>
<td>Disorder</td>
<td>--</td>
<td>Poor combination</td>
</tr>
</tbody>
</table>

Table 1: Qualitative classification table of rock mass integrity.

Figure 11: Integrity zone of the slope outcrop rock mass in J and D areas.
blocks in these areas are highly broken due to artificial reasons.

3.3. Failure Mode Analysis of the Mine Slope. Through field investigation, it is found that the main stope of the Weibei limestone mine is consistent with the failure type, which is toppling deformation failure, and the geological geometric model of toppling deformation failure of its antitoppling strata is shown in Figure 12.

Suppose that the total number of rock layers is \( n \), from the bottom of the slope to the top of the slope, they are recorded as the 1, 2, 3, \( \cdots \), \( n \) rock layers. Taking any block \( i \) from the reverse dip slope for analysis, the block \( i \) is affected not only by its own gravity \( G \) but also by the lateral extrusion force \( \sigma_H \) and gravity \( G_z \) exerted by the block \( i + 1 \). \( T \) and \( F \) are the components of interlayer forces along the stratum inclination and perpendicular to the stratum direction, respectively. The force analysis of any point \( B \) in block \( i \) is carried out. Then, the components of \( \sigma_H \) and \( G_z \) along and perpendicular to the stratum dip and the interlayer friction force are

\[
\begin{align*}
T &= T_1 - T_2 = \sigma_H \cos \beta - G_z \sin \beta \\
&= \gamma[H + (L - x)] \sin \beta[(K \cos \beta - \sin \beta)], \\
F &= F_1 + F_2 = \sigma_H \sin \beta + G_z \cos \beta \\
&= \gamma[H + (L - x)] \sin \beta[(K \sin \beta + \cos \beta)], \\
f &= \mu F = \mu \gamma[H + (L - x)] \sin \beta[(K \sin \beta + \cos \beta)].
\end{align*}
\]

Regarding the \( i \)th rock layer as a cantilever beam, the thickness of the rock layer is \( h \), the length is \( l \), and the width is \( b \). Then, the rock layer gravity per unit length \( G \) is \( G = \gamma hb \). Then, \( G \) is decomposed into two components \( G_X \) and \( G_Y \) along the \( X \) and \( Y \) directions, where \( G_X \) causes the bending of the rock and \( G_Y \) causes the axial compression of the rock. The force causing the bending deformation of the rock stratum is the force perpendicular to the axis of the rock stratum, including the gravity component \( G_X \) and the force \( F \) caused by the upper rock stratum; then, the bending moment \( M \) at any point \( B \) in the rock stratum is

\[
\begin{align*}
M &= M_G + M_F = \frac{1}{2} \gamma hb \cos \beta(L - x)^2 \\
&\quad + \frac{1}{2} H[K \sin \beta + \cos \beta](L - x)^2 \\
&\quad + \frac{1}{2} \gamma \sin \beta(K \sin \beta + \cos \beta)(L - x)^3.
\end{align*}
\]

(2)

According to the geometric size of the rock strata, the bending stiffness of the rock strata can be obtained.

\[
WX = \frac{1}{6} bh^2.
\]

(3)

During the bending process, the tensile stress on the upper boundary of the \( i \)th rock layer is

\[
\sigma = \frac{M_{x}}{W_{x}} = \frac{3 \gamma \cos \beta(L - x)^2}{h} + \frac{3 \gamma H[K \sin \beta + \cos \beta](L - x)^2}{bh^2} \\
&\quad + \frac{\gamma \sin \beta(K \sin \beta + \cos \beta)(L - x)^3}{bh^3}.
\]

(4)

When the tensile stress on the upper boundary of the strata is greater than the tensile strength of the strata, the strata collapse.

The slope of the limestone mine in Weibei is relatively steep, and the surface of the hill is mainly attached with a soft loess layer and heavily weathered mudstone layer. Most of the rock strata are exposed outside, among which the thickness of the strongly weathered and weathered layer is about 2 m, and the cracks are developed. Based on the previous research results of this type of mine slope by scholars, combined with the analysis of the actual situation, it can be seen that, in addition to bending and toppling failure on the surface of the limestone mine slope in the Weibei area, there will also be the following three failure modes if no timely measures are taken for treatment:
3.3.1. Toppling Failure along the Joint Plane. The joints parallel to the slope surface develop at the back edge of the slope so that the surface water will invade into the slope body from the joints in this layer. The whole process will accelerate the development of the fissures. Once the joint cracks develop to a certain extent, the drainage channel will be formed underground and the groundwater will be connected. As a result, under heavy rainfall weather, if the groundwater cannot be drained quickly, it is possible to form high hydrostatic pressure at the slope head and generate external thrust on the surface rock mass. Under the combined action of the inclined structural plane inside the slope, the rock mass may topple and fail.

3.3.2. Combined Failure along Joints and Planes. When the excavation slope reaches a certain depth, the rock and soil will be unstable. Due to the compression of the overlying rock, the rock and dirt in the lower part will be bent so that the inclination structure with a smaller angle will deflect towards the outside of the slope.

3.3.3. Failure Occurs along the Outward-Inclined Structural Plane. Different causes of extraversion structural planes lead
to significant differences in their physical and mechanical properties. Some extraversion structural planes are mainly composed of minor transverse fractures of each rock layer. The central structural plane is the fracture opening of the rock layer, which leads to the poor connectivity and integrity of the structural aircraft. The shear strength of the rock mass is relatively small.

4. NPR Constant-Resistance Large-Deformation Anchor Cable and Deep Sliding Surface Shear Force Monitoring Method

4.1. NPR Anchor Cable Structure. The macro-NPR anchor cable is different from the traditional PR anchor cable [42]. It has the constant resistance, and large deformation mechanical characteristics of “the thicker the cable are pulled,” and its structural composition is shown in Figure 13. The stable resistance large deformation bolt is composed of a constant resistance device, rod body, and tray. The continuous resistance sleeve and the continuous resistance body constitute the essential regular group device in the whole structure. The internal surface of the constant-resistance sleeve and the external surface of the rod body adopt the threaded system, which can also reduce the weight of the bolt. The critical point of the design parameters of the whole device is to ensure that the material strength of the constant-resistance sleeve is lower than that of the continuous resistance body. This is to avoid the friction damage of the ongoing resistance body caused by the quiet strength when the constant resistance body slips in the constant-resistance sleeve, which will significantly impact the stable resistance performance of the news anchor.

4.2. The Composition of the Shear Force Monitoring System. The shear force indoor monitoring system mainly includes the Beidou satellite receiver, GPRS data receiver, server, automatic data processing, analysis system, three-dimensional automatic search, and display equipment (Figure 14) to receive and process the data transmitted on site. The final data is displayed on the screen, and the slope stability can be monitored at all times to ensure the safety of the personnel and equipment on site.

The equipment of the shear force outdoor monitoring system mainly includes the NPR anchor cable with constant resistance and large deformation, mechanical signal acquisition, and transmitter device, followed by the antenna, solar...
panel, battery, anchor pier, and vertical rod (Figure 14). Their function is to receive mechanical signals, realize the transformation of automated calls to digital signals, and transmit them to the laboratory background through the Beidou satellite device to realize the real-time monitoring of slope force changes.

4.3. Installation of the Monitoring System and Analysis of the Monitoring Curve. Shear force monitoring points are installed at the foot of the first step slope and the foot of the second step slope, in the limestone mine. The installation position is shown in Figure 15, in which the length of the anchor cable is 30 m, the incident angle is 25°, and the pre-loading force is 30 T.

The installation positions and monitoring curves of shear force monitoring equipment in the Weibei area are shown in the figure as follows. It can be seen in Figure 16 that after the installation of the reinforced early-warning equipment, the unstable slip surface of the reinforced slope is basically in a stable state after a small range of force fluctuations and its force value is maintained between 270 kN and 280 kN and the field reinforcement effect is noticeable.

5. Conclusions

The study of slope stability and dangerous zoning is the subject of mine production technology, which belongs to applied research. However, due to the highly harsh engineering geological conditions of the limestone mine in Weibei, the slope caused by blasting quarrying in the early stage is seriously deformed. The research approaches of engineering geology in mining areas and the comprehensive treatment measures the of limestone slope are particularly significant to the development of mining technology and enrich scientific theories. They are summarized as follows:

(1) A systematic geological survey of the Weibei limestone mine main stope, south stope, and north slope is carried out by using the high-precision line survey method. Four survey lines were accumulated, and the total stroke was 506 m. A total of 86 groups of significant joints, eight dikes, and one outlet point were recorded. The rock mass has high integrity, with comprehensive zoning (A) and relatively comprehensive zoning (B) accounting for 79%.

(2) The failure mode of slope landslide in the Weibei limestone mine. The south stope and the north stope are mainly composed of two failure modes: multifactor-induced toppling deformation failure and weak local layer-controlled toppling sliding failure. Due to its high terrain and many fractures in the upper rock mass, the main failure modes of the main stope can be divided into three ways: toppling failure along the joint plane, combined failure along the joint and aircraft, and failure along the extension structural plane.

(3) Using NPR anchor cable reinforcement monitoring and an early-warning system, a typical limestone mine in Weibei area is designed and successfully applied. The field monitoring curve shows that the force value is basically maintained between 270 kN and 280 kN and the reinforcement effect is remarkable.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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