Slope failure mechanism affected by mining subsidence: a case study of highway slopes in Yangquan, Shanxi Province, China

Zhang Chao, Li Tiefeng, Han Xudong

Center for Hydrogeology and Environmental Geology Survey, CGS, 1305 Qiyilu, Jingxiu District, 071051 Baoding, People’s Republic of China

Abstract. This paper presents details of highway slopes affected by a mining subsidence event that occurred in the Yangquan coal mining area of China in 2016. To ascertain the developmental characteristics of surface deformation, a few methods were applied for investigation and monitoring, such as multiple field investigations, unmanned aerial vehicle measurements, and time-series interferometric synthetic-aperture radar techniques. An accurate numerical simulation was conducted on two slopes for stability analysis and mining subsidence prediction. Results show that the mining subsidence developed from south to north, which was consistent with the mining direction; two subsidence centers were distributed on the ground, and the north one was located in the southeast slope foot of the highway. The influence of the mining subsidence whose subsidence magnitude reached 4 m is obviously different on both sides of the highway. Although the rock and soil structure were damaged seriously, the northwest slope was completely unstable, whereas the southeast slope remained standing. The differences were studied to illuminate that slope instability is not only due to the mechanical properties of rock mass decrease dramatically but also relates to the direction of horizontal traction force, the spatial distribution of the working face, and the effective free surface of the slope. This paper presents a case of mining landslide failure for researchers.

Keywords: Coal mining subsidence, Mining landslide, Non-contact monitoring methods, Finite element method, Numerical simulation, Failure mechanism

1. Introduction

Mining subsidence is a recurrent source of damage to ground surface, artificial slope, infrastructure, and other environmental features (Can et al.,2012; Ghabraie et al.,2017). An inverse model of the effects of underground coal mining on the ground surface is necessary, especially in a typical area or situation (Salmi et al.,2015; Deck et al.,2018). Many mining landslides have occurred around the world, resulting in significant losses in life and property, such as the Frank Slide in Canada, slope deformation in the Czech Republic, and landslides in a South Wales coalfield (Bentley and Siddle.,1996; Cruden et al.,2006; Marschalko et al.,2012). Many mining landslides have also occurred in China because of large-scale resource mining in recent years, such as the Lianziya rockslide in Hubei, the Jiweishan rockslide in Chongqing, and the Hancheng landslide in Shanxi (Gu, 1988; Liu et al., 1995; Xu, et al., 2009; Yin, 2010). However, reliably predicting mining subsidence and slope failure is still a challenge because of the complexities of this problem (Li Tengfei et al.,2011; Sainsbury, 2012; Salmi et al., 2017).

Several estimation methods have been developed for predicting mining subsidence, such as empirical methods, influence function methods, numerical modeling, and physical models (Dai et
al., 2010; Unlu et al., 2013; Ren et al., 2014; Ghabraie et al., 2015). Several methods for slope stability analysis have also been developed, such as limit equilibrium method, numerical modeling, and physical models (Zheng, 2012; Jiao, et al., 2013; Lu, et al., 2013; Zheng, et al., 2015; Zhao, et al., 2020). The numerical and physical modeling method can elucidate the mechanism of dynamic surface deformation, whereas the other methods cannot. The precision of the two methods depends on accurate geologic structure and geotechnical property data, which require extensive preparatory work. The numerical method is more widely used than physical simulation to assess mining subsidence and landslide stability; it can perform appropriate simulations under complex excavation geometries, rugged topography, and various stratigraphic structures (Corkum and Board, 2016; Salmi et al., 2017; Sepehri et al., 2017; Hamdi et al., 2018; Cheng et al., 2018; Katz et al., 2014; Viero et al., 2018). The method can be subdivided into finite element method and discrete element method, both of which are appropriate approaches for analyzing the mechanism of subsidence and landslides induced by mining (Xu rt al., 2016; Vanneschi et al., 2018).

In this paper, the numerical method based on field geological survey data is conducted to model the whole process of surface deformation and slope failure characteristics to reveal the failure mechanism induced by single-seam long-wall mining. A few monitoring methods, including multiple field surveys and measurements, unmanned aerial vehicle (UAV) measurements, and time-series interferometric synthetic-aperture radar (InSAR), were implemented to monitor the surface deformation, and their results can be compared with the simulation results.

2. Description of the mine

2.1. Characteristics of rock masses

The study area is located northeast of Qinshui coalfield, a large Carboniferous–Permian coalfield in China, in a hilly topography. Drilling data collected from coal mining enterprises showed that the stratum at the top is Quaternary loess soil, and the strata at a deeper location are Neogene red clay, Permain and Carboniferous thick sandstone, sandy shale, muddy limestone, and coal seam. The mechanical properties of rock masses vary greatly in depth, and the engineering geological conditions are relatively complex.

In accordance with the differences in lithology and engineering geological characteristics, 12 layers were classified to ensure the accuracy of this research (Table 1). Layer5, layer9, layer10, and layer11 are stable and continuous, and the thicknesses of the rock strata change minimally. The thicknesses of rock strata vary greatly in layer6, layer7, and layer8, thinning out in some areas. The top of layer4 is denuded, and the thickness of the rock stratum changes greatly. Both layer2 and layer3 are almost denuded in the western area of the region.

| Geologic age | Number | Stratum                                | Average thickness (m) | Stratigraphic development characteristics                           | Engineering geological characteristics                      |
|--------------|--------|----------------------------------------|-----------------------|---------------------------------------------------------------------|-----------------------------------------------------------|
| QN           | 1      | Loess soil and red clay                | 13.2                  | Relatively thin in the hillside; the thickness is generally less than 8 m. But in the valley, it could be up to 30 m. | Loose soil, with vertical joints and large pores.          |
| PNX          | 2      | Thin sandstone and shale sandwiched with thick sandstone | 15.2                  | Denuded, distributed locally.                                         | Poor mechanical properties in the thin sandstone and shale, and relatively good in the thick |
| No. | Rock Type | Percentage | Description |
|-----|-----------|------------|-------------|
| 3   | Gray medium-grained sandstone | 4.6 | Denuded, distributed locally. The rock mass is weathered, the joints and cracks are relatively developed, with general mechanical properties. |
| 4   | Siltstone, carbonaceous shale and 4# coal | 25.7 | Partially eroded, distributed in most of the study area. Weathering in the rock mass, with poor mechanical properties. |
| 5   | Gray medium-grained sandstone | 18.5 | The layer is thick, stable, and continuous. |
| 6   | Thin sandstone, shale sandwiched with 8# coal and 9# coal | 13.2 | Large variations in rock thickness, partially sandwiched with thick layers of sandstone in the shape of a lens, the 8# and 9# coals are pinched out in some areas. The lenticular sandstone and coal seams are weathered, with cracks; thin sandstone and shale are strongly weathered, joints and cracks are developed, and the mechanical properties are poor. |
| 7   | Thin-medium fine-grained sandstone and shale interbed | 23.5 | The rock formations vary greatly. In some areas, the sandstone gradually thickens up to several meters, and the sandstone and shale in some areas are distributed in the form of 10 cm interbedded layers. The sandstone is relatively hard, weathered in the rock mass, thin-middle layered, with joints and cracks; the shale is strongly weathered, thin layered, flaky, with well-developed joints and cracks and poor mechanical properties. |
| 8   | Thin-medium medium-grained sandstone and shale interbed | 22.5 | The rock formations vary greatly. In some areas, the sandstone gradually thickens up to several meters, and the sandstone and shale in some areas are interbedded. The thickness of the sandstone is significantly thicker than layer7. Medium-grained sandstone is hard, medium-thick layered, with joints and cracks; the shale is strongly weathered, thin layered, flaky, with well-developed joints and cracks and poor mechanical properties. |
| 9   | Gray-white coarse sandstone | 8.6 | The layer is thick, stable, and continuous. The rock is hard, weathered in the rock mass, thick layered, with joints and cracks. |
| 10  | Gray-black sandy shale, siltstone, and | 18.2 | The layer is thick, stable, and continuous, mainly. The rock is hard, the rock mass is slightly weathered, with few... |
impure limestone composed of gray-black sandy shale and siltstone, with partial impure limestone, joints and cracks, and the integrity is good.

| Layer | Coal Seam | Thickness |
|-------|-----------|-----------|
| 11    | 15#       | 5.7       |
| 12    | Sandstone and shale | 75.0       |

2.2. Geological structure

The strata are generally controlled by a fold structure in the NNE direction in this area. In accordance with a small geological unit (Figure 1), Hecun anticline and Waweng syncline had a parallel distribution in the deep portion of this area, with a NE 27° trend, a distance of 1 km between the two fold cores, and an average stratigraphic dip direction and dip angle of 117° and 8.53°, respectively. The strata in the Hecun anticline are thin and gradually thicken to the southeast, reaching the maximum thickness in the Waweng syncline. The terrain on the surface is generally low in the northwest and high in the southeast, within a 50 m height difference. In the northwest, the soil stratum is thick, reaching up to 30 m, distributed around rivers and gullies, and gradually thins to less than 8 m in the southeast hillside. Therefore, the strata in the northwest are generally thin and the overlying strata are denuded seriously, resulting in the complete absence of the siltstone and shale at the top of the early Permian.

2.3. Hydrogeological condition

Four aquifers are distributed in this area from the top to the bottom: Quaternary pore water aquifer, Permian fissure water aquifer, Carboniferous fissure water aquifer, and Ordovician karstic water aquifer. The water level of Ordovician karstic water is about 200 m below the No. 15 coal, and no hydraulic pressure of confined water exists.

2.4. Mining situation
The 8# and 9# coal seams are thin, discontinuous, and unexploited in this area. The mining company mined the 15# coal seam by comprehensive mechanized coal mining method from March to September 2016. The long-wall mining method was adopted for the extracted panel named 15422, which was 405 m long and 150 m wide, while the completely collapsed method was adopted for roof management. The buried depth of the 15# coal seam is from 70 m to 140 m below the ground surface, causing serious surface deformation. Construction of the highway above the 15# coal seam started in 2014; the roadbed was leveling at that time, and mining subsidence caused a series of harmful effects, such as roadbed subsidence, cracking, and artificial slope instability. The groundwater infiltrating into the extracted panel along the weathering joints and fissures in bedrock above the 15# coal seam was completely extracted and discharged. Therefore, the influence of groundwater is weak, and the mining subsidence is mainly controlled by engineering geological conditions.

3. Investigation of surface deformation

3.1. Destruction
Ground subsidence lagged behind coal mining significantly due to the difference in thickness and mechanical properties of the overlying strata upon the coal seam. Two subsidence centers named No. 1 and No. 2 are present in farmland and roadbed, forming in early May and late July, respectively. The No. 1 subsidence center developed rapidly and sank 4 m in a few days, after which the rate of deformation slowed down and entered a slow progress stage. The No. 2 subsidence center also developed rapidly but sank 3 m in a few days, and then the rate of deformation slowed down and entered a slow progress stage similarly.

Two landslides on the northwest slope of the highway were caused by mining subsidence in June and July 2016. One of them was 10 m long, 20 m wide, and 3 m thick, and the other one was 15 m long, 60 m wide, and 8 m thick. The occurrence of landslides poses a threat to the safety of the highway. Since then, the northwest slope has continued to be unstable. Eventually, engineering measures were taken to smooth it out in 2018. The elevation has dropped by 7 m due to mining subsidence and ground leveling, being only 3 m higher than the roadbed. However, the stability of the southeast slope is much better. Aside from slope surface cleaning, no more engineering measures are needed to reinforce it.
3.2. Monitoring methods and results

The topography of the study area changed greatly because of mining subsidence and human activities in the next three years. Such activities include excavation of the northwest slope and earth filling for the roadbed by highway builders, filling the mining subsidence on the south of the highway by coal mine enterprises, and leveling off the farmland by local residents. Two non-contact methods were implemented, namely, UAV and time-series InSAR measurements, to research the variant characteristics with time of the destruction.

3.2.1. UAV measurements

On the basis of a surveying control network, UX5 HP type UAV from Trimble was used to measure the topography in August 2016. The flight altitude was set to 500 m from the surface, and the resolution reached 20 cm. A DJI Phantom 4 RTK was used to measure the topography in October 2018 by using the default control network; the flight altitude was set to 150 m, and the resolution reached 4 cm. The fissures are visible in the high-resolution image.

![Image: UAV remote sensing images of mining subsidence](image)

**Figure 3.** Remote sensing images of UAV measuring.

The roadbed began to sink and crack violently because of coal mining subsidence, and two slopes on the northwest slope of the highway are unstable. According to the UAV image on August 3, 2016, the planar features of coal mining subsidence are as follows: Two subsidence centers are located in farmland and roadbed, with the No. 1 subsidence center sinking 4 m and being flooded, while the No. 2 subsidence center sank 3 m. Identifiable fissures are distributed linearly or in an arc around the subsidence centers, with the combination of fissures around the No. 1 subsidence center being annular and the combination of fissures around the No. 2 subsidence center being fan shaped. Two landslides on the north slope were generated on June 23 and July 16; landslide1 was 20 m wide, and landslide2 was 60 m wide.

Self-healing caused most fissures to close by themselves, and residual fissures appeared θ-shaped on the plane in October 2018.

3.2.2. Time-series InSAR monitoring

SAR technology has obvious advantages in dealing with surface deformation monitoring, and it has been widely used by scholars in monitoring volcanic activity, seismic activity, land subsidence, landslide, and coal mining subsidence (Chen Y et al., 2017; Massonnet D. et al., 1993; F. Raspini et al., 2016; Alex et al., 2015). Referring to the technologies of processing SAR data, a few methods have
been proposed, such as D-InSAR, PS-InSAR, and SBAS. Although InSAR has been used in coal mining subsidence monitoring and achieved some satisfactory results (Zhiwei Li, et al.,2015; Lei Wang, et al.,2018; Zefa Yang, et al.,2018), nonlinearity, rapid deformations, and sudden collapses caused by coal mining are difficult to monitor effectively (Fan, et al.,2018).

Eight RADARSAT-2 images spanning the period from June 16 to December 1, 2016 were acquired to monitor the surface deformation more accurately. The repetitive observation period of the RADARSAT-2 is 24 days, which enables an increase in the frequency of deformation monitoring. The range and azimuth of pixel spacing are about 1.5 and 2.0 m, respectively. Only image pairs with the smallest temporal and spatial baseline were selected to preserve a high coherence for all image pairs. Seven image pairs, which were constructed from two adjacent images, were generated.

![Figure 4](image_url)

**Figure 4.** Time-series InSAR monitoring from June to December.

As shown in the figures, no data were detected in the south of the subsidence because the terrain was changed considerably by the landfill. At the beginning, the surface subsidence values of the northern area were small, and then gradually increased to 11.5 cm, which was significantly smaller than the actual subsidence values. Landslide1 and landslide2 are not obviously captured in Figures 4a and Figure 4b; only the deformation distributed in the northwest slope is shown. The No. 2 subsidence center is not shown in Figure 4c due to large deformation, but the subsidence boundary determined by InSAR is the same as the UAV measurement in the northern area. This finding indicates that time-series InSAR is an effective technique in detecting coal mining subsidence and that delineating the range of subsidence is better than monitoring the magnitude of subsidence. In addition, the area along the southeast slope foot of the highway can be deduced to have a large magnitude of subsidence. In other words, if the results calculated by InSAR appear annular and no data are shown in the central area, then the value of subsidence in the central area may be larger than that in the surrounding area.

4. Numerical modeling

4.1 Model building

Finite element method and discrete element method are suitable for simulating coal mining subsidence and slope failure. The finite element method is close to the movement modes of fracture zone, bending
zone, and landslide, whereas the discrete element method is close to the movement modes of caving zone and rockfall. In this study, the finite element method was selected to research the process of deformation both underground and on the surface by using the engineering software FLAC3D.

For a more detailed illumination of the coal mining subsidence, a 3D model was built by FLAC 5.0, and two topic profiles were selected to show the surface deformation. Profile A-A′ was along the mining direction of the extracted panel and passed through the two coal mining subsidence centers, with a length of 600 m. Profile B-B′ was perpendicular to Profile A-A′ and passed through the No. 2 coal mining subsidence center, with a length of 450 m. The models were composed of blocks, the height of which was generally controlled between 4–8 m, and the length and width were set as 5 m.

4.2 Geotechnical parameters

The subsidence range of coal mining confirmed by investigation and monitoring was taken as the basis for the division. The rock and soil inside the range of subsidence were disturbed, while the rock and soil outside the range of subsidence were not. An engineering geological survey was carried out on a typical open-pit slope near the coal mining subsidence. The engineering geological characteristics were ascertained, including the lithology of strata and the joints and crack development degree, and then the geotechnical parameters of rock masses were estimated by Hoek-Brown failure criterion. In this study, the Geological Strength Index (GSI) was used to classify the rock masses and estimate their mechanical parameters. The GSI is perhaps one of the most widely used rock mass classification methods for computing rock mass mechanical parameters, which can contribute to the mechanical behavior of the rock masses (Marinos et al., 2005). The diagrams proposed by Hoek and Marinos (Hoek, 2007) were used to estimate the GSI and other parameters of rock masses, in which the adverse effects of water and weathering on the rock mass behavior were taken into account. Parameter D depicts the damage caused by the excavation method, and mi is the intact rock constant in the Hoek-Brown failure criterion.

The Hoek-Brown failure criterion can also be used to derive the equivalent Mohr–Coulomb shear strength parameters of a rock mass or figure out the deformation modulus (\(E_m\)) and the uniaxial compressive strength (\(\sigma_{ci}\)) of a rock mass (Marinos and Hoek, 2000; Hoek and Diederichs, 2006). Generally, the values of equivalent c and equivalent \(\varphi\) are obtained by linear regression within a given range of principal stress, and the rock mass deformation modulus is evaluated by using formula 1, as suggested by Hoek et al.

\[
\begin{align*}
E_m (GPa) &= \left(1 - \frac{n}{2}\right) \left(\frac{\sigma_{ci}}{100}\right)^{1/2} 10^{\frac{55-10}{46}} \quad (\sigma_{ci} \leq 100MPa) \\
E_m (GPa) &= \left(1 - \frac{n}{2}\right) 10^{\frac{55-10}{46}} \quad (\sigma_{ci} > 100MPa)
\end{align*}
\]

Mohr–Coulomb failure criterion was used to estimate soil mass, such as layer1, and Hoek-Brown failure criterion was used to estimate rock masses from layer2 to layer12. The value of parameter \(D\), referred to from previous experience (Nan et al., 2015), in the caving zone, fracture zone, bending zone, and influence zone of the coal floor were set as 1, 0.8, 0.5, and 0.3, respectively.

| Number | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | \(\mu\) | \(C\) (MPa) | \(\Phi\) (°) |
|--------|-----------------|--------------------|---------------------|-------|----------|---------|
| layer1 | 1380            | 0.03               | 0.01                | 0.3   | 0.01     | 15      |

**Table 2.** Rock mechanic parameters of layer1

| Number | Density (kg/m³) | \(\sigma_{ci}\) (MPa) | \(\mu\) | GSI | \(m_i\) | \(D\) |
|--------|-----------------|------------------------|-------|-----|--------|-------|
| layer2 | 2610            | 40.3                   | 0.24  | 40  | 7      | 0.5   |
| layer3 | 2630            | 75.6                   | 0.23  | 50  | 15     | 0.5   |

**Table 3.** Hoek-Brown mechanical parameters of rock mass
| Layer | Depth (m) | OCR (m) | Water Depth (m) | Thickness (m) | Water Content (%) | Porosity (%) |
|-------|-----------|---------|-----------------|---------------|-------------------|--------------|
| 4     | 2610      | 44.0    | 0.24            | 40            | 7                 | 0.8          |
| 5     | 2630      | 75.6    | 0.23            | 50            | 17                | 0.8          |
| 6     | 2570      | 29.3    | 0.28            | 40            | 4                 | 0.8          |
| 7     | 2610      | 47.0    | 0.24            | 45            | 10                | 0.8          |
| 8     | 2610      | 49.2    | 0.24            | 50            | 12                | 0.8          |
| 9     | 2630      | 110.6   | 0.23            | 50            | 19                | 0.8          |
| 10    | 2690      | 65.3    | 0.22            | 60            | 8                 | 1            |
| 11    | 1459      | 33.7    | 0.24            | 50            | 4                 | 0.8          |
| 12    | 2610      | 53.2    | 0.24            | 60            | 7                 | 0.3          |

4.3 Simulated results

![Figure 5. Numerical simulation results of the subsidence.](image)

In the process of model running, the No. 1 subsidence center appeared, gradually moved eastward, and finally reached 16 m east of the central line of the working face. The No. 2 subsidence center was blocked by the eastern slope, appearing at the foot of the slope. The northwest slope of the highway was evidently affected by coal mining subsidence and induced slope failure in the most affected section, which is called landslide2.

When the process of subsidence was completed, the Liu Village coal mining subsidence presented an elliptical shape, with a long axis of 489 m, a short axis of 269 m, and an area of $11.25 \times 10^4$ m$^2$. The maximum vertical displacement exceeded 4 m and was located on the center line of the working face and gradually decreased toward the edge of the subsidence. The maximum magnitude of the horizontal displacement distributed along the inner edge of coal mining subsidence exceeded 1.5 m in the northwest slope, whereas it was no more than 1 m in the southeast slope.

4.4 Failure mechanism

Scholars generally believe that mining landslides occur because mining subsidence causes the destruction of the overlying rock mass structure, after which the rock mass mechanical parameters...
...decrease sharply, ultimately leading to slope instability. But in this case, the damage of the rock mass structure is only one of the reasons. The magnitude of the subsidence of the southeast slope, which is close to the subsidence center, is greater than that of the northwest slope. According to common sense, the damage degree of the rock mass should be greater and the southeast slope should be more unstable, but that is not the case. In fact, the southeast slope was stable, whereas the northwest slope was unstable. This fact illustrates that, aside from the destruction of the rock mass structure, the horizontal tension generated during the subsidence process is one of the important factors that lead to the failure of the northwest slope. A simple model was built to illustrate this issue (Figure 6).

![Figure 6. Spatial distribution of X displacement, stress–strength, and strain increment after mining.](image)

The largest displacement is located in the left slope and exceeded 2 m. The stress–strength ratio is eight times greater than it was before it was disturbed in the left slope foot. The maximum principal strain increment is focused on the back edge of the left slope; therefore, instability occurs easily in the left slope. In contrast, the possibility of instability is much lower because of the lower magnitude of displacement, stress–strength, and strain increment of the right slope. These factors depend on the spatial distribution of the working face and the mining direction. One endpoint of the working face shown in Figure 6 is under the left slope, the other endpoint is at the lower right of the right slope, and the mining direction is from right to left, thus causing the displacement. If the conditions change, then the consequence will be different.

For this case, the difference in stability between the two slopes can be concluded to depend on three factors: mining subsidence caused a sharp decline in the mechanical properties of the slope rock mass; the direction of horizontal traction force and horizontal displacement induced by mining subsidence may or may not be a key factor in the slope failure; and the spatial distribution of the working face and the effective free surface of the slope play an important role.

5. Conclusions and suggestions
Compared with traditional monitoring methods, the non-contacted monitoring methods have obvious advantages in monitoring coal mining subsidence, such as full coverage, high precision, and being maintenance free. High-resolution images and high-precision digital elevation models can provide considerable information about coal mining subsidence. InSAR is an effective tool to detect coal mining subsidence and to explore the timing and magnitude of their motion. Satellite passes are now frequent and the resolution is sufficiently high to allow time-series analyses of movements as small as tens of millimeters for surface deformation.

Physical modeling techniques can present visualized evolutionary characteristics of mining subsidence in deep strata and measure the stress distribution conveniently in simplified geological conditions, thus playing a considerable role in promoting mechanism analysis. The conclusions are as follows: 1. Subsidence is a real case given a complicated terrain, engineering geological conditions, boundary conditions, and mining conditions. The difference from the usual coal mining subsidence is that two subsidence centers appear on the surface. The mechanism is that the bedrock surface presents...
a W shape in the A-A’ Profile. One of the low terrain is on the highway, and the other is in the southern valley, with the high terrain between them serving as a block. 2. Landslide1, which occurred on a small scale at the intersection of the highway and a small road, resulted in the slope surface being exposed on two sides and weathered the surface rock mass to a high degree, resulting in poor mechanical parameters. Failure occurred because of the influence of coal mining subsidence; 3. Landslide2, which occurred in the northwest slope and coincided with the mining subsidence, was affected by three aspects: a. the coal mining subsidence destroyed the rock and soil structure and reduced the mechanical properties of the slope, b. the horizontal traction force caused by the coal mining subsidence caused a large horizontal displacement of the slope, and c. the effective free surface of the artificial slope created beneficial conditions for the occurrence of landslide.

Affected by coal mining subsidence, the stability of the southeast slope declined and may fail under extreme abnormal weather conditions. Therefore, engineering measures need to be taken on the southeast slope to ensure the safety of the highway.

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