Deformation Failure Mechanism and Motion Laws of Near-horizontal Thick-layer with Thin-layer Columnar Dangerous Rock Mass in the Chishui Red Bed Area

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Abstract. The collapse of dangerous rock masses, either due to natural causes (such as weathering by rain) or anthropogenic factors (such as engineering construction in the rock area), poses a threat to both life and property. Therefore, investigating deformation failure mechanisms and determining the movement characteristics of the rock masses after collapse can provide practical guidance for conducting linear projects while taking adequate measures to prevent the collapse. In this study, a dangerous rock mass on the right side of the Yuanhou Toll Station of the Rongzun Expressway was used to study the deformation and failure mechanism of near-horizontal and thick layer with thin-layer columnar dangerous rock masses in the Chishui red bed area. A high-definition 3D-surface model was generated by using unmanned aerial vehicle (UAV) tilt photography technology to obtain an aerial image of dangerous rock masses with spatial coordinates in the research area. The three-point method was used to interpret the structural surface of the dangerous rock mass based on the 3D model. A model for the deformation and failure of dangerous rock masses was developed via an engineering geological analysis. We simulated and analyzed the cause of deformation and failure of dangerous rock masses using FLAC3D software. In addition, the motions of rock fall were studied by performing simulations using Rockfall software. From the interpretation of the 3D model of the UAV, the dangerous rock mass developed two sets of dominant structural planes that were nearly vertical and perpendicular to the stratum level, cutting the rock mass into cuboids. Based on the analysis of a stereographic projection, the dangerous rock mass was in an unstable state. The results showed that the dangerous rock mass had a high stress concentration in the middle and lower soft rock, which is likely due to dumping collapse under self-weight and differential weathering. Moreover, rock fall has a 60% probability of causing damage to the road below the rock mass if it collapses, threatening the safety of passing vehicles and people's lives and property.

1. Introduction

The red layer is a clastic sedimentary rock layer mainly composed of terrestrial sediments and lacustrine facies. It is reddish in color because of the presence of high iron content in the rock minerals. The red beds in China are mainly distributed in the southwest and northwest regions, including Yun, Gui, Chuan, Gansu, and Qinghai, as well as the central and southern regions [1]. The rock layer in the
red bed area is divided into soft and hard parts. The latter comprises mainly sandstone, while the soft part is mainly mudstone. The soft part has a weak permeability and low strength [2]. This is the reason for the engineering properties of the red bed rock mass being poor. Hence, geological disasters often occur when engineering construction is carried out in red bed areas. Chishui City faces several types of geological disasters, including landslides, debris flows, ground subsidence, and collapse. Collapse refers to the phenomenon where the rock and soil body on a steep slope cuts into huge rock blocks by joint fissures and suddenly falls out of the parent rock under the action of gravity or other external dynamic forces, such as falling down, rolling over, and falling [3-6]. Collapse disasters have a devastating effect on the residents, buildings, roads, and bridges within its reach. For example, the collapse in Kaili Longchang Town, Guizhou Province resulted in the death of 5 people in 2013; the collapse in Nayong, Guizhou Province caused 35 deaths in 2017. Therefore, a collapse disaster can have a huge adverse effect on human life and property [7-8]. Current research on the collapse of dangerous rock masses mainly involves investigating collapse failure mechanisms, motion characteristics, risk assessment, and protection technology [9-11]. Analyzing the deformation failure mechanism and predicting the movement characteristics of the collapse can provide guidance for the protection of completed linear projects and the selection of linear projects to be conducted in the Chishui red bed area.

Research on the collapse of dangerous rock masses requires on-site investigations. However, most of the dangerous rock masses that are likely to collapse are situated in high and steep locations, often concealed, and difficult to survey. This leads to high risk and low efficiency of the manual on-site investigations [12]. Unmanned aerial vehicles (UAVs) are emerging as a tool that is increasingly being used in geological disaster investigation to acquire geographic information that allows high precision, high efficiency, and low risk interventions, especially for investigating locations that are difficult to reach. For example, Chen Z X et al. [13] used a UAV to investigate roads around high-risk dangerous rock masses in a strongly earthquake-prone area, and they studied the stability of 19 dangerous rock masses. Wang X L et al. [14] predicted the movement characteristics of rock that collapsed on a mountainous transmission station project using aerial remote sensing and UAV aerial survey technology. Peng S Q et al. [15] used a UAV to obtain a high-resolution digital surface model of the collapse of Pusa Village in Nayong County in Guizhou. They studied the particle size of the collapsed bodies via statistical analysis.

Research on the deformation and failure mechanism and the motion characteristics of dangerous rock masses mainly includes physical simulations, numerical simulations, and theoretical calculations. Among them, numerical simulation is the most commonly used method. For example, Liu C Z et al. [16] simulated the Ludian redstone rock collapse area using FLAC3D software, in which the deformation and failure mechanisms were studied to determine the spatial and temporal distribution of displacement, velocity, and acceleration. Rong Z P et al. [17] constructed a three-dimensional (3D) geological model using the PFC3D simulation environment to simulate the collapse and calculate the movement path of the dangerous rock mass as well as investigate the two-dimensional movement process with Rockfall. They obtained calculation results for the leaping height, impact energy, and rock block velocity. Through Rockyfor3D, Wang S et al. [18] obtained the impact range of the collapse of the Shexing Village section of the Qinghai–Tibet Railway. They also determined the rock’s reaching probability, dominant motion path, and the height and kinetic energy of the stone as well as the distance slope of the dangerous rock block for the dominant motion path. Through DAN-W, Yang L W et al. [19] calculated the movement process of the collapsed debris flow. They found that the movement of the collapsed debris flow is usually about 50 s, the average thickness of the accumulated mass of debris reached 2 m, the maximum velocity is 11.5 m/s, and the maximum impact distance reached 315 m.

As an engineering case study, the dangerous columnar rock mass on the right side of the Yuanhou Toll Station of the Rongzun Expressway was investigated in this study. Aerial photogrammetry on the research area was obtained using a UAV, and a high-definition 3D surface model was built based on the aerial images and the interpretation of the rock structure plane information. We simulated the
dangerous rock mass and studied its deformation and failure mechanisms, combined with on-site investigation and UAV data using FLAC3D. Using Rockfall, we analyzed the movement characteristics and impact range of dangerous rock masses. Our study provides a basis for the design of prevention and control measures for collapse disasters.

2. Study area
The study area is located in Caijiagen Village, Yuanhou Town, Chishui City, Guizhou Province, approximately 600 m from the Yuanhou Toll Station of the Rongzun Expressway. The central geographic coordinates, E105°56′49.58″ and N28°21′23.85″, are in the middle and low mountain valleys and deeply cuts the Chishui River. The river banks have mostly steep slopes and cliffs. This area belongs to the mid-subtropical warm and humid monsoon climate zone. Rainfall and sunshine is experienced in the same season. The average rainfall is 1,286.8 mm. The rainy season is mainly from May to September, accounting for 68% of the rainfall experienced during the entire year. The dangerous rock mass, situated at a height of approximately 100 m above the road, ranges from 308 m to 347 m in height, and is cut into a cuboid rock mass (with dimensions: 7 m deep, 12 m wide, and 39 m high) by a crack of about 2 m in width by the trailing edge. The upper formation is the Cretaceous Jiading Group (Kjd), which is purple with gray, gray–purple, and thick medium-fine grain feldspar quartz sandstone. The lower formation is the Jurassic Upper Penglaizhen Formation (J3p), dark purple with purple thin grain sandstone, which is interbedded with dark purple and fuchsia mudstones of different thicknesses. Sandstones are mostly thick-bedded with a large bedding thickness. The attitude of the rocks is 315°∠2°. The dangerous rock mass has a gentle slope, cliff, and a steep slope from top to bottom. There is vegetation on the upper gentle slope with a coverage rate of over 90%, and the range of the slope gradient is 25°–40°. In the middle, and forming a cliff, the rock bed is without vegetation coverage, and its slope angle is close to 90°. On the he slope angle of the lower steep slope is 50°–60°. Two scarp s are formed because of the construction and excavation of the country road and the Rongzun Expressway. The specific conditions of the dangerous rock mass are shown in Figure 1, and the section of the dangerous rock mass of the slope is shown in Figure 2.
3. Establishment of UAV 3D model and structural plane interpretation

3.1. 3D geological modelling

The UAV low-altitude photogrammetry technology is a remote sensing system that uses a UAV as a flying platform. It carries sensors for obtaining ground information. We shot images of the dangerous rock masses in the study area using multi-route, multi-angle, and omnidirectional imaging techniques using the UAV. Based on previous experience, the overlap rate of the UAV’s course should not be less than 80%, and the overlap rate of the lateral direction should not be less than 70%. Several photographs of the slope where the dangerous rock masses were located were taken. Based on the high-definition digital photos containing the geographic coordinates of the shooting point, a virtual 3D model of the study area was constructed using the oblique photogrammetric method. Data such as space and volume size and structural plane parameters of the dangerous rock mass were extracted from the omnidirectional 3D model.

The slope of the study area suggests it can be classified as an eroded low-mountain valley landform, where there is a large height difference and flourishing vegetation. This makes automatic drone photography difficult. Therefore, a low-altitude flight was manually conducted to obtain a total of 570 high-definition photographs of the slope in the study area after considering many factors, such as slope height, length, inclination, vegetation, and high-altitude power lines.

Based on the spatial coordinates from the high-definition 3D photographs, we built a 3D digital surface model of the study area using Agisoft PhotoScan (Figure 3). A detailed statistical analysis inside the development of slope structural planes was conducted and the distribution of dangerous rock mass and space information was obtained. These can greatly improve work efficiency and avoid risks associated with field investigations.

3.2. Structural plane interpretation

The structural plane is a geological interface in a certain direction with low mechanical strength and bidirectional extension. It is composed of three elements: strike, tendency, and dip. It is a relatively weak part of the rock mass with a low mechanical strength, and it often serves as the control surface
that determines the overall stability of the rock mass. The traditional method for acquiring rock mass structural planes is by having workers on-site to take measurements using a compass. In this study, based on the 3D model created with the UAV data, an indoor omnidirectional dangerous rock surface structure was determined. The basic principle of structural plane interpretation is based on obtaining 3D coordinates of the three non-collinear feature points in the structural plane and obtaining the occurrence of the rock’s structural plane through mathematical calculation (Figure 4).

![Figure 4. Structural plane occurrence diagram](image)

If the structural plane equation is set to $Z = AX + BY + C$, one normal vector of the structural plane (whichever is upward) should be $\vec{n} = (-A, -B, 1)$. Assuming that the coordinates of $n (n \geq 3)$ are non-collinear, feature points are extracted in the same structural plane to solve for A, B, and C using the least squares method, as shown in equation (1):

$$
\begin{bmatrix}
A \\
B \\
C
\end{bmatrix} = 
\left[
\begin{array}{ccc}
X_1 Y_1 & X_1 Y_1 \\ X_2 Y_2 & X_2 Y_2 \\ \vdots & \vdots \\ X_n Y_n & X_n Y_n \\
\end{array}
\right]^T
\left[
\begin{array}{ccc}
X_1 Y_1 \\ X_2 Y_2 \\ \vdots \\ X_n Y_n \\
\end{array}
\right]^{-1}
\times
\left[
\begin{array}{ccc}
X_1 Y_1 \\ X_2 Y_2 \\ \vdots \\ X_n Y_n \\
\end{array}
\right]
\left[
\begin{array}{c}
Z_1 \\
Z_2 \\
\vdots \\
Z_n \\
\end{array}
\right]
$$

(1)

The mathematical model for calculating the structural plane’s inclination $\beta$ and dip $\alpha$ using the normal vector [20] is

(2) When $A = 0$,

$$
\begin{cases}
\alpha = |\arctan B| \\
\beta = \left\{ \begin{array}{l}
\frac{\pi}{2}, \; B < 0 \\
3\frac{\pi}{2}, \; B > 0 \\
\forall, \; B = 0
\end{array} \right.
\end{cases}
$$

(3) When $A \neq 0$,

$$
\begin{cases}
\alpha = \left|\frac{\arctan \sqrt{A^2 + B^2}}{\arctan(B/A)}\right| \\
\beta = \left\{ \begin{array}{l}
\arctan(B/A), \; A < 0, \; B \leq 0 \\
\arctan(B/A) + 2\pi, \; A < 0, \; B > 0 \\
\arctan(B/A) + \pi, \; A > 0
\end{array} \right.
\end{cases}
$$

A statistical analysis of the structural surface of the dangerous rock mass based on the 3D model of the UAV was conducted. Three non-collinear points were taken on the structural surface to acquire their
spatial coordinates and the occurrence of the structural surface was obtained through a programming calculation (Figure 5). A total of 65 sets of structural plane data were obtained to draw the isopycnic graph of the structural plane and the tendency rose diagram (Figure 6).

From the interpretation results, the dangerous rock mass mainly comprises two sets of dominant structural planes, which tend to be nearly vertical and cut the dangerous rock mass into a long column. The structural plane parameters are shown in table 1.

| Serial number | The average occurrence | The joint density (n/m) | Opening (mm) | Filling state | Connectivity |
|---------------|------------------------|-------------------------|--------------|---------------|--------------|
| J1            | 18° 78°                | 1                       | 20–2000      | Partially argillaceous filling | Through the rock |
| J2            | 304° 73°               | 5                       | 10–30        | Without filling            | Through the rock |
4. Dangerous rock mass stability evaluation and deformation failure mode analysis

4.1. Dangerous rock mass stability evaluation
The dangerous rock masses in the study area are sand and mudstones with different thicknesses and interbedded layers. Furthermore, the occurrence of rock layers is $315^\circ \angle 2^\circ$. According to the interpretation results of the structural plane of the 3D model generated using the UAV data, the dangerous rock mass comprises two sets of structural planes controlled by J1: $18^\circ \angle 78^\circ$ and J2: $304^\circ \angle 73^\circ$. The slope tendency of the dangerous rock mass was $28^\circ$, the slope angle of the upper gentle slope was $30^\circ$, and the lower steep slope was $86^\circ$. The stereographic projection map and its geological model map are shown in Figure 7.

![Figure 7. Stereographic projection and geological model diagram of the structural plane of the dangerous rock mass](image)

From the analysis of the stereographic projection, the intersection point of the two structural planes (J1 and J2) is on the same side as the slope of the slope projection, that is, between the gentle slope and the steep slope. The slope angle smaller than the steep slope is larger than the slope angle of the upper gentle slope. The intersection of the structural planes is exposed on the upper gentle slope, and the cutting body belongs to a relatively unstable structure. Hence, the entire dangerous rock mass is in an unstable state.

4.2. Deformation failure mode analysis
The dangerous rock mass in the study area is a columnar body that is cut by two sets of structural planes formed by the front edge’s free space owing to the undercutting of the Chishui River. The unloading fissures were formed at the rear edge. The lithology is interbedded with sand and mudstone. According to the field investigation and the interpretation of the 3D model of the UAV, the weathering rate of the mudstone in the middle of the dangerous rock mass is faster, forming a deep concave rock cavity. This is because of the difference in the weathering rate of sandstone and mudstone. The morphology of the bigger one on the upper. If it continues to be affected by factors such as rainwater and surface water erosion and groundwater softening, the differential weathering will continue to deepen the concave rock cavity. Upon reaching a certain depth, the central mudstone cannot bear the huge weight of the upper rock body. In addition, under special conditions such as rainstorms and earthquakes, dumping collapse can easily occur (Figure 8).
5. Numerical Simulation Study

5.1. FLAC 3D numerical simulation

5.1.1. Model establishment. The development of a model for the dangerous rock mass was mainly conducted using MADIS software because of certain defects of FLAC3D in the establishment of complex geological models. The geological model was then imported using the MADIS TO FLAC3D plug-in into FLAC3D for calculations [21]. The calculation model comprised 24,936 entity units (zones) and 6,943 grid points (grid points) (Figure 9).

5.1.2. Boundary conditions. We set the boundaries of the calculation model as follows: the bottom is fixed; the natural slope and the top are free; the sliding hinge supports the left and right sides; and the horizontal direction is constrained except in the vertical direction for producing vertical displacements. The calculation model load mainly considers the weight of the soil.

5.1.3. Material parameters. The material was selected as the elastoplastic mechanical model and according to the Mohr–Coulomb strength criterion. The physical and mechanical parameters of the rock mass were obtained based on data from laboratory rock mechanics tests (Table 2) combined with similar engineering experience of numerical simulations in the same geographic area.

| Lithology   | ρ (Kg.m⁻³) | E (GPa) | μ | φ (°) | c (Mpa) |
|-------------|------------|--------|---|------|--------|
| Mudstone    | 2.340      | 4.59   | 0.3 | 22   | 0.2    |
| Sandstone   | 2.500      | 7.75   | 0.2 | 28   | 0.6    |

Figure 8. The development process of the collapse and failure of a dangerous rock mass

Figure 9. Diagram showing the numerical calculation model for the dangerous rock mass

Table 2. Material parameters
5.1.4. Analysis of calculation results. Figures 10 and 11 show the maximum and minimum principal stress cloud diagrams, respectively. As shown, the principal stress field is generally manifested as a stress field dominated by self-weight stress and is mainly controlled by lithology. From bottom to top, the principal stress gradually decreases in magnitude. Since it is mainly controlled by lithology, the stress concentration phenomenon is more evident in a certain range near the mudstone in the middle and lower parts of the dangerous rock mass.

![Figure 10. Contour of Maximum Principal Stress](image1)

![Figure 11. Contour of Minimum Principal Stress](image2)

Figure 12 shows a cloud diagram of the maximum shear strain. As shown, the shear strain increase in the middle of the dangerous rock mass is large, especially in the middle of the columnar dangerous rock mass. This phenomenon is particularly noticeable and can be seen that a certain amount in the middle is . There is a red–yellow band in the range, which suggests an increase in shear strain. The lithology at this location is mudstone, and the dangerous rock mass may be destroyed first at this location.
The displacement of the columnar dangerous rock mass decreases to zero, and the maximum displacement can reach 0.79 m at the top (Figure 13).

A large plastic zone is present in the lower-middle part of the dangerous rock mass as well as in the mudstone interbed. This is an indication that the dangerous rock mass may undergo plastic failure along its lower-middle part under special working conditions (Figure 14).

5.2. *Simulation study on the movement characteristics of dangerous rock mass*

In this study, Rockfall software was used to simulate the trajectory of rolling stones of the dangerous rock mass [22]. Some basic parameters related to slopes and falling rocks, such as the moving path, energy distribution, and bounce height of rolling stones on slopes, were inputted and changes were
predicted by the simulation. This provides an intuitive and effective basis for the study of the impact of collapse disasters and the design of protective measures.

5.2.1. Parameter setting. The slope of the dangerous rock mass’s location can be divided into seven sections from top to bottom through the analysis of the 3D model of the study area: vegetation soil, bedrock outcrop, vegetation soil, asphalt highway pavement, vegetation soil, asphalt highway pavement, and vegetation soil. The normal recovery coefficient (Rn) and tangential recovery coefficient (Rt) of each section were selected according to the slope’s characteristics. The specific parameters were determined and combined with the results of previous studies. The basic parameters of the side slope are presented Table 3.

| Slope characteristics          | Coefficient of normal restitution (Rn) | Coefficient of tangential restitution (Rt) |
|-------------------------------|----------------------------------------|------------------------------------------|
| Bedrock outcrops              | 0.35                                   | 0.85                                     |
| Soil with vegetation          | 0.3                                    | 0.8                                      |
| Asphalt                       | 0.4                                    | 0.9                                      |

5.2.2. Analysis of calculation results. The number of rolling stones was set to 100 in this simulation without the initial movement and rotation speed. The simulated movement process of the rolling stones on the slope is shown in Figures 15 and 16.
According to the distribution curve in Figure 16, the stones rolled down the slope after the first bounce at 39 m, and then, they collided with the slope, slope scarp, rural road, and Rongzun Expressway at 66, 101, 117, and 136 m, respectively. Hence, the speed and kinetic energy of the dangerous rock mass peak appeared at 39, 66, 101, 117, and 136 m, respectively. Since the rolling stones are accelerated before the collision, the speed and kinetic energy peak at the collision point. A decrease in speed and kinetic energy is experienced due to energy loss during collisions. According to the bounce height curve, the rolling stones’ speed and kinetic energy reduce to minimum values owing to collision with the slope. Its kinetic energy is converted into gravitational potential energy when the bounce height reaches its peak; this causes the kinetic energy to decrease. On reaching the peak, the falling rock gradually changes from ascending motion to descending motion; thus, the speed significantly decreases. The total kinetic energy of the dangerous rock mass falling to 132 m is 355988 KJ at a speed of 16.6 m/s when reaching the highway. The velocity, bounce height, and kinetic energy are all reduced to 0 at 171 m away from the collapse point, and the rolling stones move to the farthest distance.

Based on the Rockfall simulation results, a histogram that shows the distribution of the locations of rolling stones after the collapse of the dangerous rock mass was plotted (Figure 17). Fifteen percent of
the rolling stones stayed on the slope, 25% landed on the rural road, 44% on the Expressway, and 16% crossed the highway and stopped on the lower slope.

The results of the study show that rolling stones have a 60% chance of reaching the highway after the collapse. They possess sufficient speed and kinetic energy to reach the highway. Serious damage to the Expressway can occur, vehicular traffic can be affected, and the safety of life and property of the people in the vehicles can be threatened.

6. Conclusions
(1) We investigated a dangerous rock mass in the Chishui Red Bed area using UAV tilt photography technology. A high-definition digital surface model was created from the photographs taken, and structural plane information of the dangerous rock mass was extracted from it. The results show that the dangerous rock mass is controlled by two sets of structural planes.
(2) A qualitative analysis of the columnar dangerous rock mass using the stereographic projection method revealed the instability of the dangerous rock mass. Because of differential weathering, the concave rock cavity continues to deepen, and the dangerous rock mass may collapse under special conditions, such as heavy rainfalls and earthquakes.
(3) The columnar dangerous rock mass has high stress concentrations in the middle and lower mudstone sections, determined by part analysis using FLAC3D. Consequently, the collapse or destruction of the dangerous rock mass may commence in these sections with high stress concentrations.
(4) Using the Rockfall software to simulate and study the characteristics of typical dangerous rock mass caving movements, we determined that rock fall has a 60% probability of causing damage to the Expressway at the foot of the slope after the collapse of the dangerous rock mass. The obtained results can play a significant guiding role in the investigation and study of dangerous rock masses located on high and steep slopes.

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