Investigation and motion characteristics analysis of dangerous rock in high and steep slope based on UAV

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Abstract. The geological conditions in Southwest China are complex, and the dangerous rock hazards developed in the high and steep slopes has extremely high harmfulness and concealment. The traditional contact survey method is difficult to find out the geological hazard effectively under the limitation of complex and changeable terrain conditions. Unmanned aerial vehicle photogrammetric system has high flexibility and can obtain high-efficient, high precision and high resolution remote sensing images of geological disaster investigation area. By using the UAV photogrammetry system, the dangerous rock mass of the intake slope of Jinping secondary hydropower station is investigated. The working principle of UAV, the acquisition of high-definition image data and the construction of 3D model are discussed, and the feasibility of using the model data obtained by the system to investigate dangerous rock mass is demonstrated. Through repeated analysis and interpretation of the 3D real-scene model, the distribution characteristics of the dangerous rock hazard points of the intake slope are found out. On this basis, four sections are selected to simulate the movement track of unstable dangerous rock mass with Rocfall software, and the movement velocity, jump height and impact energy of different characteristic points of falling rock are calculated quantitatively with the formula. The research results provide an important reference value for the investigation of dangerous rock mass of high and steep slope in southwest China.

1. Preface

Southwest China is rich in hydropower resources, with steep natural bank slopes and narrow river valleys. Under the strong unloading effect, the shallow rock mass of the slope has poor stability due to the cutting of the structural surface, and is prone to geological disasters such as dangerous rock [1]. In recent years, large-scale hydropower projects have been built with high and steep slopes, which will cause huge economic losses in case of unstable rock falling. The traditional survey method belongs to single point and contact survey [2]. For geologists, not only the field work is large, the accuracy is low, the efficiency is low, and the cost is high, but also there are great potential safety problems [3]. The photogrammetric system of UAV takes UAV as the flight platform, which can give full play to the super mobility of UAV remote sensing in low visibility and small areas that is difficult for investigators to reach [4]. In recent years, the use of UAV for geological hazard investigation has been more and more recognized by the industry[5]. Yang Lilong [6] used small and light UAV to model aerial photography, and got the attribute information of rock mass on the experimental slope. Wang Jingjing[7] and others used UAV tilt photography and image processing technology to obtain more
effective influence factors of geological disaster area, and used weighted deterministic factor method and information model method to evaluate the susceptibility of geological disaster. Xiao Gang [5] and others developed a system to collect the information of slope cracks in high and dangerous rock mass according to the gray scale and spatial characteristics presented in the UAV images, and applied it to practical projects. Wang Dong [3] and others proposed the method of combining the volume measurement of the structure surface of the dangerous rock mass through theoretical analysis, field tests and other means, and applied it to the investigation of the dangerous rock mass of the high and steep slope of Chengdu-Kunming railway. Wang Shuaiyong [4] and others applied UAV remote sensing to the area where the laohuzui landslide was located, and studied the application process of this method in landslide exploration in strong earthquake areas. Zhang Qianqi, Huang Haining [8-9] and others analyzed the evolution process of unstable rock mass by using UAV photography technology, and calculated the structural surface information of critical rock mass. Fazio N.L [10] and others applied UAV 3D photogrammetry to the evaluation of the coastal stability of discontinuous rock mass, and compared the structural discontinuity detected by photogrammetry with the traditional in situ measurement method. Jordan a. Carey [11] and others combined UAV photography with digital photogrammetry of moving structures to detect the Scenic Drive landslide in La Honda, California, and calculated that the landslide caused a material displacement of 3000m³.

In this paper, the technique of UAV tilt photography is used to investigate the dangerous rock mass in the slope that cannot be reached by the investigators. On this basis, the numerical simulation and formula calculation method are further used to analyze the movement characteristics of the unstable rock mass.

2. Overview of the research area
The intake slope of the diversion tunnel of the Jinping II Hydropower Station is located at the downstream of Jingfeng bridge on the right bank of Yalong River, with the bottom plate elevation of 1618m and four 12m diameter headrace tunnels arranged. The river section in the project area flows to the south-east direction (N5° to 10° E), and the river valley is about 120m wide at the normal pool level. The slope elevation above 1700m is 55-75°, which cannot be reached by manpower. The formation lithology is mainly green schist of Lower Triassic (T₁) and marble of Middle Triassic Zagunao formation (T₂z). The rock strata incline steeply in the direction of NE. The unloading effect of shallow slope rock mass is strong. The overall appearance of the intake slope is shown in Figure 1. In the rainy season of 2018, some dangerous rocks on the side slope of the outgoing line yard of Jinping II hydropower station collapsed over the previous passive network and smashed into the outgoing line yard.

Fortunately, no loss of personnel and property was caused, but the safety risk is prominent. It is urgent to carry out dangerous rock hazard investigation on the intake slope and other important slopes of the diversion tunnel of the hydropower station, so as to provide geological basis for the protection engineering.

3. UAV photogrammetry of dangerous rock slope
3.1. UAV camera system
The UAV photography system is mainly composed of the air part, the ground part and the data processing part [4]. The traditional remote sensing data is mainly from vertical or small inclination satellite images, which is difficult to meet the requirements of geological disaster investigation under the influence of shadow and occlusion. The UAV remote sensing system is equipped with a high-resolution digital camera with vertical and tilt photography functions. Under the condition of ensuring the overlap rate, the photos with different angles and coordinate information of dangerous rock can be obtained. These images can more truly reflect the multi angle profile and texture information of ground objects and meet the needs of 3D modeling [12].
3.2. **Tilt photogrammetry technology**

Tilt photogrammetry technology can combine the remote sensing images collected from the top (positive) and tilt (oblique) angles to reflect the real contour and texture information of the ground object more vividly and provide data basis for establishing 3D solid model of survey area [9]. The main steps of processing the collected image are as follows: high precision detection of camera, dense matching of multi angle image, joint adjustment of multi angle image, creation of digital surface model (DSM), correction of real projection image, 3D modeling, etc.

In the 3D model, the slope gradient, slope tendency, height difference and elevation value can be read directly, which is helpful to analyze the stability and movement characteristics of dangerous rock mass.

3.3. **Remote sensing survey of intake slope by UAV**

3.3.1. **Data acquisition.** According to the characteristics of the intake slope and UAV, the YS-1pro fixed-wing UAV with five lenses and the DJI M600pro multi rotor UAV are used for two take-off and landing flights. Firstly, the UAV with fixed wing with long endurance and high flight height is used for aerial capture of the whole slope, and then the UAV with multi rotor with better imaging effect is used for aerial capture of the slope with elevation below 2160m. The whole flight area is 0.7km², The course and side overlap of UAV route are 85% and 80% respectively (see Figure 2). The main parameters of the two UAVs and the camera are shown in Table 1. The resolution of slope image is 0.1-0.2m.

3.3.2. **Data processing.** In the process of image data processing, the 3D modeling software Smart3D capture is used to model the intake slope. In order to ensure the correct data format and data integrity, it is necessary to preprocess the collected aerial photography and image control measurement data according to the set format. The processed data can be imported into the software for 3D modeling[13]. The specific steps include: three-dimensional measurement, geometric processing, multi-view matching, triangular net construction, automatic texturing [2]. The established slope model is shown in the Figure 3.

3.3.3. **Interpretation of results.** By using the software of acute3dviewer to browse the three-dimensional model established by the three-dimensional point cloud data of the slope, we can fully grasp the real scene of the geological disaster body and its surroundings, and get the accurate spatial position, geometric shape and geological characteristics of any dangerous rock mass in the dangerous rock section. Therefore, it can provide important parameters for the accurate calculation of the stability of dangerous rock, the trajectory, velocity and impact energy of rock falling and bouncing after

![Figure 1. Overall appearance of inlet slope.](image1)

![Figure 2. UAV track chart.](image2)
stripping the parent rock, and the obtained data can provide important parameters for the design of prevention measures. At the same time, the existing protective measures and their damage degree in the early stage of the project area can be comprehensively checked through the three-dimensional model, so as to make a more efficient prevention and control design.

Table 1. Main parameters of UAV and camera.

| Related parameters of fixed-wing UAV | Multi-rotor UAV Related Parameters | Camera related parameters |
|-------------------------------------|------------------------------------|--------------------------|
| **Related parameters**              | **Related parameters**             | **Camera type**          |
| **parameter**                       | **parameter**                      | **SONY ILCE-5100**       |
| Aircraft wingspan                   | Number of axes                     |                          |
| 2.2m                                | Six axis                           |                          |
| Mission load                        | Wheelbase                          |                          |
| 1kg                                 | 1.1m                               |                          |
| Flight duration                     | Flight duration                    |                          |
| 2h                                  | 30min                              |                          |
| Wind resistance                     | Wind resistance                    |                          |
| 11m/s                               | 8m/s                               |                          |
| Flying speed                        | Flying speed                       |                          |
| 86.4 km/h                           | 65km/h                             |                          |
| Flight height                       | Flight height                      |                          |
| 6000m                               | 2500m                              |                          |
| Camera type                         | Image resolution                   |                          |
| SONY ILCE-5100                      | 7360×4912                          |                          |
| Image resolution                   | Sensor type                        |                          |
| 7360×4912                           | Exmor APS HD CMOS                   |                          |
| Sensor size / mm                    | Exposure time                      |                          |
| 35.9×24                             | 1/1250s                            |                          |
| Focal length / mm                   | Focal length / mm                   |                          |
| 35                                  | 35                                 |                          |

Figure 3. Construction of spatial 3D model of slope.

Figure 4 shows the dangerous rock mass W4 of the intake slope, which is located about 449m above the water inlet with an elevation of 2038m. According to the image analysis, the dangerous rock mass is controlled by three groups of structural planes LX1, LX2 and LX3. Steep structural surface (LX1, Lx2) cuts both sides of W4, and gently inclined structural surface (LX3) makes its lower part free. The fracture at the back edge of the dangerous rock has not been penetrated yet, and it is in a
poor stability state at present. Under the influence of external factors such as rain wash, softening, gradual weathering and seismic force, the fracture at the back edge will continue to expand and open, and the dangerous rock will eventually lose stability.

Figure 4. W4 remote sensing image.  Figure 5. Distribution of dangerous rock of inlet slope.

According to the macro judgment factors of dangerous rock [14], remote sensing interpretation and classification of other dangerous rock hidden danger points in the whole intake slope area are carried out. A total of 3 monomer dangerous rocks and 17 dangerous rock groups are counted (marked in Figure 5). According to the development of dangerous rock mass and engineering influence, the intake slope of diversion tunnel is divided into dangerous rock I area and scattered dangerous rock.

4. Analysis of dangerous rock movement characteristics of intake slope

4.1. Two-dimensional simulation of rockfall motion characteristics

Rocfall is based on the principle of probability calculation and analysis in the software. By placing a certain number of falling rocks on the slope for statistics and simulation, the complete motion trajectory of the unstable rock mass in the slope can be obtained [15]. According to the distribution characteristics and terrain characteristics of the dangerous rock in the upper part of the inlet slope, four sections were selected to simulate the movement trajectory of the dangerous rock in each section by Rocfall in two dimensions. The profile and rock distribution are shown in Figure 6. The tangential damping coefficient $R_t$ and the normal damping coefficient $R_n$ of the slope take values of 0.81 and 0.32, respectively. The number of simulated rockfall rolls per section is 100.

According to the simulation results, the slope of the 1740-1800m elevation section on the 1-1′ profile is relatively gentle, and the falling rocks have basically no bounce. The slope of the 1680-1740m elevation section is steep. Falling rocks jump out at this slope section. The falling rocks bounce in the elevation range of 1650-1680 m, and some of the falling rocks prance (Figure 7a). The slope on the 2-2′ profile is relatively gentle, and the falling rocks have basically no bounce on this slope (Figure 7b). On the 3-3′ profile, the slope at the altitude of 1835-2040m is relatively slow, and the bounce phenomenon of falling rocks is not obvious. From 1645 to 1835m, the slope is relatively steep, the
bounces phenomenon begins to occur and the bouncing height gradually increases, part of the falling stone pranced(Figure 7c). On the 4-4’ section, the slope is relatively slow at the height of 1760-1890m. The falling rocks have basically no bounce on this slope, and there is only a leap at 1800-1835m. the slope of 1670-1760 m elevation section suddenly becomes steep, the falling rock bounce and prance in this slope section(Figure 7d).

4.2. Calculation of rockfall movement characteristics

Falling stone protection measures should be set in the lower prance position. According to the simulation results, quantitative calculations are performed on the movement speed, bounce height, and kinetic energy of instability rocks at the positions where the terrain is relatively gentle and the bounce height is low. Piecewise calculation models were built in each section(Figure 7).

According to the simulation results, the kinematic velocity, prancing height and kinetic energy of the unstable rock were quantitatively calculated at the locations where the topography of each section was slow and the jumping height was low.

4.2.1. Calculation of rockfall motion speed. The terminal speed for each slope is calculated as follows.

\[ V_1 = \mu_1 \sqrt{2gh} \]
\[ V_2 = \sqrt{\frac{V_1^2 \times \cos^2(\alpha_2 - \alpha_1) + \mu_2^2 \times 2gH_2}{\cos^2(\alpha_2 - \alpha_1) + \mu_2^2}} \]
\[ V_i = \sqrt{V_{i-1}^2 \times \cos^2(\alpha_i - \alpha_{i-1}) + \mu_i^2 \times 2gH_i} \]

\[ \mu = \sqrt{1 - K\tan \alpha} \]
\[ \epsilon = \mu \sqrt{2g} \]

In the formula:

- H——Falling height of stone (m); g——Gravitational acceleration (m / s²); \( \alpha \)——The slope of a hillside (°); k——Resistance characteristic coefficient; \( \epsilon \)——Speed coefficient; \( \mu \)——coefficient.
4.2.2. Calculation of Rockfall. Prance As shown in Figure 8, the trajectory equation is:

\[ y = \frac{gx^2}{2V_0 \sin^2 \beta} + x \cdot ctg \beta \]

\[ \beta = \frac{200 + 2\alpha (1 - \frac{\alpha}{45})}{\sqrt{V_i}} \]

In the formula:

- \( V_0 \) — Rockfall rebound speed (m/s);
- \( \beta \) — The angle between the direction of \( V_0 \) and the vertical direction (°);
Figure 8. Trajectory curve of falling rocks.

By analyzing the movement track, the vertical deviation $h$ and horizontal deviation $l$ of rockfall to the slope reach the maximum when $x_1 = 0.5x_0$, and the calculation is based on the following formula:

$$l_{\text{max}} = \frac{V_0^2 (\tan \alpha - \cot \beta)^2}{2g \tan \alpha (1 + \cot^2 \beta)}$$

$$h_{\text{max}} = l_{\text{max}} \tan \alpha = \frac{V_0^2 (\tan \alpha - \cot \beta)^2}{2g (1 + \cot^2 \beta)}$$

$L_{\text{max}}$ and $h_{\text{max}}$ values are calculated, then the height $h_p$ of the retaining structure after considering the safety height is:

$$h_p = h_{\text{max}} + h_0$$

$h_0$ —— Safety value and the calculation value of intake slope is 1.0m.

4.2.3. Calculation of rockfall energy. The motion of falling rock on the slope is complex. In order to calculate the energy of falling rock, the motion state can be simplified to the combination of translation and rotation. The total kinetic energy $E$ of falling rocks is the sum of translational kinetic energy $E_1$ and rotational kinetic energy $E_2$. According to experience, the translational kinetic energy is 5 times of the rotational kinetic energy. In conclusion:

$$E = E_1 + E_2 = \frac{3}{5} m v^2$$

$m$ —— Quality of rockfall (kg);

$v$ —— Speed of rockfall (m/s).

According to the above calculation method, the rockfall motion characteristics of the dangerous rock mass of the intake slope are calculated. As W16, W19 and W20 are far away from hydraulic structures, no calculation has been made. The calculation results of other dangerous rocks are shown in Table 2.

According to the analysis of calculation results, if dangerous rocks W1 and W2 lose their stability, the rockfall bounce height is large, and they are close to the permanent hydraulic structure of the water intake, their movement track may threaten the safety of the water intake, and their stability is poor, so the risk is moderate.

The dangerous rock in area I is generally high, with a maximum rebound height of 2.26m, a maximum energy of 3835.5kj, and the impact force is large. In addition, the threat objects are mainly permanent hydraulic structures under the slope, so the risk is medium to large.

The development slope of dangerous rock w17-w18 is relatively steep. Although the bounce height is not high after instability, the falling rock will roll into the ditch and move along the ditch, which will eventually threaten the permanent hydraulic structure of the water intake. In addition, the kinetic energy is large, so the risk is medium to large.
Table 2. Calculation table of rockfall motion characteristics.

| Falling Rock Number | Falling point speed $V$ (m/s) | Jumping height $h_{\text{max}}$ (m) | Blocking height $h_p$ (m) | Rockfall energy $E$ (kJ) |
|---------------------|-------------------------------|-----------------------------------|-------------------------|------------------------|
| W1                  | 23.90                         | 1.96                              | 2.96                    | 1871.28                |
| W2                  | 15.30                         | 1.89                              | 2.89                    | 805.45                 |
| W3                  | 38.01                         | 0.14                              | 1.14                    | 1964.15                |
| W4                  | 44.99                         | 1.08                              | 2.08                    | 1956.07                |
| W5                  | 43.35                         | 0.74                              | 1.74                    | 1969.63                |
| W6                  | 44.99                         | 1.50                              | 2.50                    | 1956.07                |
| W7                  | 23.76                         | 0.79                              | 1.79                    | 2588.43                |
| W8                  | 38.88                         | 0.52                              | 1.52                    | 1361.79                |
| W9                  | 20.71                         | 1.18                              | 2.18                    | 2740.56                |
| W10                 | 27.18                         | 0.40                              | 1.40                    | 2903.96                |
| W11                 | 19.90                         | 2.10                              | 3.10                    | 402.07                 |
| W12                 | 19.36                         | 2.17                              | 3.17                    | 933.14                 |
| W13                 | 29.95                         | 0.96                              | 1.96                    | 3835.50                |
| W14                 | 18.51                         | 2.26                              | 3.26                    | 1515.17                |
| W15                 | 13.30                         | 0.91                              | 1.91                    | 678.18                 |
| W17                 | 27.86                         | 1.53                              | 2.53                    | 2707.16                |
| W18                 | 23.73                         | 1.59                              | 2.59                    | 2408.16                |

There are some errors when measuring the parameters of dangerous rock mass on the 3D model through manual operation. In addition, the selected section line cannot be completely consistent with the actual rolling path of rockfall. Therefore, there are inevitable errors in the calculation results. In order to reduce the impact of errors, the interpretation measurement of dangerous rock mass and the selection of section line should be as accurate as possible.

5. Conclusion

(1) UAV remote sensing technology can solve the geological disaster investigation limited by complex terrain conditions. By building a high-resolution 3D model of the investigation area, not only the work efficiency is improved, the intensity and risk of field work are reduced, but also the geological disaster situation can be repeatedly analyzed, and then the attribute information can be accurately extracted.

(2) According to remote sensing interpretation and classification, there are 3 monomer dangerous rocks and 17 dangerous rock groups. Their stability is poor, which seriously threatens the permanent hydraulic structures below. The intake slope is divided into dangerous rock area I and scattered dangerous rocks.

(3) Using two-dimensional Rocfall software to simulate the movement track of the dangerous rock body interpreted by remote sensing, the results show that the falling rock basically has no bounce in the gentle slope section, and the phenomenon of bounce and even prance occurred when the slope was large.

(4) Through quantitative calculation of falling rock motion velocity, bounce height and impact energy, the maximum bounce height of falling rock is 2.26 m, the impact energy is generally between 1000 to 3000 kj, and the maximum resch 3835.5kj. The quantitative calculation results can provide data basis for prevention and control engineering design.

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