Dangerous Rockfall Protection Technology Research on High Slopes of Large-Scale Underground Cavern Group Outlets of a Hydropower Station

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Abstract. In the construction of hydropower projects in southwestern China, the powerhouse, diversion tunnel, tailrace tunnel, access tunnel, and other structures are often located underground in cavern groups. The high slopes of the outlets of these large cavern groups are often characterized by steep terrain, high elevation, and frequent rockfalls, which seriously threaten the safety of construction and operation personnel. Therefore, it is urgent to carry out research on protection technology for dangerous rockfalls on underground excavation outlet slopes. In this paper, Uncrewed Aerial Vehicle (UAV) survey technology is applied. First, large-scale three-dimensional (3D) terrain data is collected by a UAV, then a Digital Orthophoto Map (DOM) and Digital Elevation Model (DEM) of the slope are obtained, and a 3D visualization is constructed. Meanwhile, an orthophoto image for detailed UAV route planning is generated. Second, according to the 3D visualization, a preliminary judgment of potentially dangerous rockfall areas is made by the engineers, and the UAV track planning for these areas is carried out. Third, refined low-altitude aerial photography is carried out on the dangerous areas according to the results of the UAV trajectory planning, and high-precision pictures are obtained. Based on the rock joints, fissures, and configurations displayed in these pictures, the areas with the most likely rockfall risks are further determined. Finally, 3D rockfall simulation software is used for rockfall simulation analysis. Comparing the rockfall interception rates and the distribution probability of rockfalls in each area under different protective net schemes, the final protective net plan is determined. The research results are applied to the design of a dangerous rockfall protection scheme on a natural slope at the outlet of a large underground hydropower station on the Dadu River, which provide a scientific basis for the setting of the protective net. The researches results can be used as reference for similar projects and provide a new idea for the design of dangerous rockfall protection measures on high slope tunnel outlets.

1. Introduction

Since the beginning of the 21st century, China’s water conservancy and hydropower industry has developed vigorously, and a number of large-scale hydropower projects have been constructed and successfully put into operation. Due to the special topography and geological conditions, most of
China’s hydropower projects are concentrated on the Jinsha, Yalong, Lancang, Dadu, and other rivers in southwest China. In the construction of these hydropower projects, the powerhouse, diversion tunnel, tailrace tunnel, access tunnel, and other structures are often located underground. The high slopes of the outlets of these large underground structures are often characterized by steep terrain, high elevation and frequent rockfalls. These characteristics seriously threaten construction and operation safety. Therefore, it is urgent to carry out research on protection technology for dangerous rockfalls on the high slopes of underground cavern group outlets.

To prevent dangerous rockfall on high slopes at the outlet of a cavern, it is necessary to monitor it first and judge its potential instability. At present, conventional slope safety monitoring, such as multipoint displacement meters, total station, Global Navigation Satellite System, etc., are all single point monitors, and these often need to lay control points on the slope, but this is difficult on a dangerous rock slope. With the rapid development and gradual maturity of three-dimensional (3D) laser scanning, close-range photography, satellite photography, and Uncrewed Aerial Vehicle (UAV) photography, new ideas are provided for solving these problems. (1) High-precision 3D laser scanning can obtain 3D point cloud data of slope surfaces [1], so it is widely used in slope engineering. For example, Zhang et al. [2] applied 3D laser scanning technology to deformation monitoring of a slope in a mining area. After data splicing, filtering, and modeling, point analysis and area analysis were used to compare and analyze detection data, and the results are consistent with the monitoring results from total stations. Ma et al. [3] regarded the volume, slope, and elevation changes of mining slopes as slope deformation factors, and verified that the calculated error of 3D laser scanning technology meets the earthwork monitoring requirements. (2) Close-range photography refers to the acquisition of target object image data measured within 300 m, and then more accurate shape and size coordinate information can be obtained without touching the target object [4]. Xiang et al. [5] compared the accuracy of close-range photogrammetry and believed that selecting an appropriate base-to-height ratio is the key to improving the accuracy. (3) As for the application of satellite technology on slopes, Liu et al. [6] used global positioning system (GPS)/pseudolites (PLs) combined positioning technology to enhance the geometric strength of satellites, proposed multiscale decomposition and reconstruction through empirical mode decomposition, and established a system trend separation model. Wang et al. [7] applied Beidou satellite positioning technology to slope monitoring and proved its accuracy and stability.

The application of these technologies in engineering has promoted the intelligence and precision of slope monitoring, and has become more and more closely integrated with slope engineering. The above technologies also have their own advantages and disadvantages. For example, 3D laser scanning technology is affected by the field of view, and blind spots are prone to appear; and close-range photography has stringent requirements for the position of the photographic equipment. When the installation is too far away or the shooting angle is too high, accuracy cannot be guaranteed; and traditional close-range measurement is dangerous due to rockfalls [8,9]. For satellite technology, due to the compilation period and cloud cover, the acquisition of real-time satellite images is easily interrupted and is greatly affected by the weather. For example, images obtained when the fog is thick are inaccurate or even unreadable [10]. The stability and endurance of UAV flights have steadily improved, and UAV aerial photography has gradually become widely used in railway maintenance, surveying and mapping, slope deformation, rockfall mitigation, and other engineering fields [11,12].

In this work, UAV aerial photography is applied to protection from dangerous rockfalls on steep slopes at the outlet of large underground cavern groups of hydropower stations. First, the principle and application steps of UAV aerial photography are introduced, including the collection of large-scale aerial photography data, 3D visualization construction, close-range aerial photography route planning, refined low-altitude aerial photography of dangerous areas, and acquisition of high-precision aerial photos. On this basis, a 3D rockfall simulation analysis is carried out. Finally, these technologies and theories are applied to the design of a protection scheme for dangerous rockfalls at the underground powerhouse outlet on the Dadu River, providing a scientific basis for the installation of a protective net.

2. UAV aerial photography technology
UAVs are uncrewed aircraft controlled by remote radio signals or an on-board computer. UAV aerial photography uses UAVs as aerial platforms carrying remote sensing equipment (such as digital cameras, light optical cameras, infrared scanners, laser scanners, magnetic measuring instruments) to obtain information, for which computers process the image information and produce images according to certain accuracy requirements.

The main steps of UAV aerial photography are shown in Figure 1.

The seven steps are as follows: (1) Large-scale image collection of slope imagery: UAVs collect large-scale images of the study area. The purpose of this step is to understand the distribution of each dangerous rock mass and the occurrence of joints and fissures. (2) Construction of 3D visualizations: 3D stitching software generates large-scale visualizations that meet the determined needs and provide a basis for subsequent short-range UAV route planning. (3) Short-range UAV route planning: the 3D pictures generated in the previous step are imported into UAV path planning software, and a reasonable route is selected according to the specific conditions of the target area. Pictures of the key areas are collected in a comprehensive and complete manner. (4) High-precision aerial photo collection: the path planning file obtained in the previous step is imported into the UAV aerial photo system to complete high-precision image collection. (5) Picture quality inspection: the pictures are evaluated for photo overlap, inclination, and rotation angle, as well as course curvature, flight altitude maintenance, and impact on clarity, etc. Pictures that do not meet the requirements are removed. (6) Aerial photography supplementary photography: if course overlap is insufficient or there are missing photographs, supplementary photography is required. It is necessary to take supplementary shots of two adjacent routes out and back during supplementary shooting. (7) High-precision 3D model construction: professional modelling software to perform refined modeling of local high-precision pictures to obtain 3D pictures of the target rock mass for subsequent analysis.

3. Principle of 3D rockfall simulation analysis

The outlets of large underground cavern groups are densely packed with engineering facilities, and vehicles and personnel are frequently in and out. Rockfalls can easily cause personal injuries, property losses, or construction schedule delays. Therefore, the need for research on the impact areas and trajectories of rockfalls is urgent. Three-dimensional rockfall simulations need to consider the influencing factors, including rock shape modeling, rock motion control formulas under freefall, and consideration of the influence of factors such as terrain conditions and forest cover.

3.1. Modeling rock shape

Rock bodies are introduced into the simulation domain coordinate frame with origin (O) as a cloud of points based in a coordinate system of their own with origin (K). The rock has three translational (linear momentum) and three rotational degrees of freedom (spin) to describe the center position of the
rock mass \( q^T = (X,Y,Z) \) at any time (t) in the terrain coordinate frame (O). Rotational motions capture the orientation of the rock’s external geometry in space. At time \( t = 0 \) the rock is released from position \( q_0^T = (X_0,Y_0,Z_0) \), which must be located some distance above the terrain, \( Z_0 > Z_m \), and thus the release height \( h_0 \) is \( Z_0 - Z_m \).

3.2. Free flight motion with gravity and gyroscopic forces

In free flight, the governing equations of motion are

\[
M \ddot{u} - h(q,u) = 0 \tag{1}
\]

\[
h(q,u) = \begin{bmatrix} F_g + D \\ G \end{bmatrix} \tag{2}
\]

where \( M \) is the constant and diagonal mass matrix (containing the mass and three moments of inertia). The vector \( u \) contains the rock’s three translational and three rotational velocities. The rock body’s motion is governed by a number of forces that determine its trajectory.

Gravitational force \( F_g \) acts globally; a drag force \( D \) is implemented to represent the effects of trees, undergrowth, and soil deformation. Gyroscopic forces \( G \) can cause rocks of irregular shape to become upright and rotate about a rolling axis. All force terms \( h \) are a function of the rock’s position \( q \) and velocity \( u \) forming the force vector \( h \).

3.3. The impact of terrain and forest vegetation

Three-dimensional rockfall simulations need to take into account the influence of terrain factors. Parameters such as hardness and rebound coefficient in different areas of the slope have a great impact on the agreement between simulation results and the actual situation. Therefore, it is necessary to set the parameters reasonably according to the actual slope conditions.

Forests are not uncommon in settings where falling rocks occur on a slope. The idea behind forest drag is that a resisting force acts on the rock’s center of mass when it is located below the vegetation drag layer height \( Z_h \). This force is linearly proportional to the rock velocity \( V_s \). The forest is parameterized by the effective height of the vegetation layer \( Z_h \) as well as the drag coefficient \( \theta_f \).

\[
F_{df} = -C_f V_s \tag{3}
\]

\[
C_f = \begin{cases} 
\theta_f & Z \leq Z_h \\
\theta_f - \frac{Z - Z_h}{x,Z > Z_h} & x,Z > Z_h 
\end{cases} \tag{4}
\]

The software provides three types of forests: Open Forest (20 m\(^2\)/ha, forest drag 250 kg/s); Medium Forest (35 m\(^2\)/ha, forest drag 500 kg/s); or Dense Forest (50 m\(^2\)/ha, forest drag 750 kg/s).

3.4. Software

This work uses RAMMS: ROCKFALL software (The authorized number is ROCKFALL bcig-0fj3-pllr-i3cf-li5m) to study rockfall trajectories. The ROCKFALL model uses a hard-contact, rigid-body approach to model rockfall trajectories in general 3D terrain. The rock/ground interactions are controlled by friction. Rockfall modeling involves six main state variables, namely three translation speeds and three rotation velocities. The software considers eight predefined terrain categories, namely: extra soft, soft, medium soft, medium, medium hard, hard, extra hard, and snow, which basically cover common slope terrain.

4. Case analysis

4.1. General engineering situation

The hydropower station project is located on Dadu River. The normal storage level of the reservoir is 1,246 m, with a total storage capacity of 20,754 million m\(^3\). The installed capacity of the power station is 1,116 MW. The powerhouse of the hydropower station is underground. The extent of the plant project along the river is composed of the switchgear, the exhaust tunnel outlet, the air shaft outlet, and the tailrace tunnel.

After removing the overburden, the engineering slope in this area is excavated with a stable slope ratio and supported by a system of bolting and shotcreting, ensuring safety. However, the natural slope
is large, high, and steep. The rock mass has a strong geological effect, and there are hazards such as flying or rolling rocks, collapses, dangerous rock masses, and mud-rock flows on the high slopes in the project construction area. Potential safety hazards are prominent. To ensure the safety of the switch station, access tunnel, exit tunnel, air intake and exhaust tunnel, and tailwater outlet during the construction and operation period as well as to avoid damage to personnel, vehicles, and equipment under the slope, it is necessary to study the natural slope of the plant location.

The main sources of danger for the slope of the underground powerhouse plant is dangerous rocks. There are 7 dangerous rock masses and 6 dangerous rocks. Among them, the No. 6 dangerous rock mass is located on the natural side slope above the access tunnel, with an elevation of 1260 m to 1330 m, a length (downhill) × width of 120 × 50 m, and a surface area of about 6000 m². The bedrock is granite, where vegetation is not developed, the bedrock is bare, and there are overhangs or caves in some parts. The upper part rock mass is relatively complete and the lower part rock mass has poor integrity. Three sets of cracks cut the rock mass into a cube shape about 10 m³, and the failure mode is planar slip. Obvious signs of collapse can be seen in the lower part dangerous rock mass. This article mainly conducts rockfall simulations on the No. 6 dangerous rock mass, and gives suggestions for setting up protective measures based on the results.

4.2. Three-dimensional trajectory simulation
Large-scale image data on the slope of the switch station along the river was collected. After generating a full-scale 3D view, the target area was identified for study of the terrain and slope characteristics. The take-off point and path of the UAV was determined to avoid colliding with trees, power transmission lines, mountains, or other obstacles and to make the target area imaging as comprehensive and clear as possible. The full-scale 3D topographic map of the switch station is shown in Figure 2.

![Figure 2. The full-scale three-dimensional topographic map.](image)

The path planning file was imported into the drone control software, and the fine flight was retraced. Than the digital elevation models (DEM) and digital orthophoto maps (DOM) are generated, as shown in Figure 3. Then modeling and trajectory simulation were performed in RAMMS:ROCKFALL software.

![Figure 3. (a) DEM and (b) DOM of No. 6 rock mass.](image)
A protective net has been set up in the area of the No. 6 dangerous rock mass. To integrate the actual slope conditions, the predefined terrain category is set to medium hardness, and 10 types of rocks of different shapes (cuboid and cuboid) and volumes are used to simulate the rocks. The trajectories of falling rocks on the slope are shown in Figure 4. The interceptions by the protective net and the distribution of falling rocks on the river, the plant area, and the road were counted, then the interception efficiency was compared to determine the optimal protection plan. The statistical results are shown in Table 1.

![Figure 4. Rockfall tracks near existing protection facilities.](image)

**Table 1.** Protection effect under existing protection facilities for No. 6 dangerous rock mass.

| Number | Shape | Volume (m³) | Distribution of falling rocks | Interception efficiency |
|--------|-------|-------------|-------------------------------|-------------------------|
|        |       |             | Interception | Plant | Road | River | Interception rate |                  |
| 0.5    | Cuboid | 66          | 31       | 1     | 0    | 0     | 67%               |                  |
| 1      |        | 65          | 33       | 0     | 0    | 0     | 66%               |                  |
| 2      |        | 67          | 30       | 1     | 0    | 0     | 68%               |                  |
| 3      |        | 69          | 26       | 3     | 0    | 0     | 70%               |                  |
| 4      |        | 72          | 21       | 3     | 0    | 0     | 75%               |                  |
| 5      |        | 63          | 33       | 2     | 0    | 0     | 64%               |                  |
| 6#     | Cuboid | 59          | 34       | 5     | 0    | 0     | 60%               | 69%              |
| 1      |        | 51          | 41       | 6     | 0    | 0     | 52%               |                  |
| 2      |        | 52          | 36       | 10    | 0    | 0     | 53%               |                  |
| 3      |        | 67          | 28       | 3     | 0    | 0     | 68%               |                  |
| 4      |        | 55          | 39       | 4     | 0    | 0     | 56%               |                  |
| 5      |        | 54          | 37       | 7     | 0    | 0     | 55%               |                  |
| 0.5    | Cube  | 66          | 31       | 1     | 0    | 0     | 67%               |                  |
| 1      |        | 65          | 33       | 0     | 0    | 0     | 66%               |                  |
| 2      |        | 67          | 30       | 1     | 0    | 0     | 68%               |                  |
| 3      |        | 69          | 26       | 3     | 0    | 0     | 70%               |                  |
| 4      |        | 72          | 21       | 3     | 0    | 0     | 75%               |                  |
| 5      |        | 63          | 33       | 2     | 0    | 0     | 64%               |                  |

Combining the rockfall trajectory image in Figure 4, a preliminary protective net plan at the intersection between the rockfalls and the slope is set up, and the optimal protective net plan is obtained through continuous adjustment. The rockfall trajectories are shown in Figure 5, and the protective effect under different working conditions is shown in Table 2.

In this study, a comprehensive analysis of falling rocks of different shapes and sizes is carried out. Under the current protection situation, the interception rate of the protective net is only about 60%, and a large number of falling rocks will impact the plant area and road. The dangerous rock mass has a serious impact on construction and power generation. Therefore, a secondary protection plan must be carried out. Rockfall simulation software is used to simulate rockfall trajectories through the design of multiple protection schemes, and the optimal net configuration is obtained. The statistics in Figure 5 and Table 2 show that after the addition of protective measures the interception rate is increased to more than 95%, the probability of falling rocks impacting the plant area is greatly reduced, and the falling speed and impact force will be greatly reduced after two interceptions by the protective net, which can effectively improve the safety of construction and operation.
Figure 5. Rockfall trajectories after adding protective facilities.

Table 2. Protection effect under added protection facilities for No. 6 dangerous rock mass.

| Number | Shape | Volume (m³) | Distribution of falling rocks | Interception efficiency |
|--------|-------|-------------|-------------------------------|-------------------------|
| 6# Cuboid | 0.5 | 92          | 6                              | 94%                     |
|        | 1    | 96          | 2                              | 98%                     |
|        | 2    | 95          | 3                              | 97%                     |
|        | 3    | 97          | 1                              | 99%                     |
|        | 4    | 96          | 2                              | 98%                     |
|        | 5    | 95          | 3                              | 97%                     |
| 6# Cube  | 0.5 | 91          | 6                              | 93%                     |
|        | 1    | 91          | 7                              | 93%                     |
|        | 2    | 95          | 3                              | 97%                     |
|        | 3    | 93          | 3                              | 95%                     |
|        | 4    | 93          | 5                              | 95%                     |
|        | 5    | 95          | 3                              | 97%                     |

5. Conclusion
In this work, UAV aerial photography is applied to protection from dangerous rockfalls on the high slope of large-scale underground cavern group outlets of hydropower stations. Applications of UAV aerial photography and 3D rockfall simulation analysis theory are carried out. These technologies and theories have been applied to the design of a protection scheme for dangerous rocks falling at the outlet of the underground powerhouse of a large hydropower station on the Dadu River. The following results have been obtained.

(1) The steps of UAV aerial photography technology for rockfall protection of high slopes include: collecting large-scale aerial photography data, constructing 3D visualizations, planning close-range aerial photography routes, refining low-altitude aerial photography of dangerous areas, and obtaining high-precision aerial pictures.

(2) In the 3D simulation of rockfall trajectories, the impact of rockfall shape simulation, free flight motion control formula, terrain conditions, forest vegetation, and other parameters are fully considered. In this work the RAMMS:ROCKFALL software is used for simulation, and parameters such as rockfall impact areas, energy and velocity graphs, and rockfall dynamic trajectories are obtained. Based on this, new protection nets at different locations were added and their protection effects are evaluated, so as to determine the optimal protection plan.

(3) In the design of the dangerous rockfall protection scheme at a large hydropower station on the Dadu River, trajectory simulations are carried out after taking pictures with a UAV. The results show that under the existing protective measures, the interception rate of falling rocks is between 50% and
70%, and nearly 30% of falling rocks will have an impact on the plant area, so new protective measures must be added. Based on the analysis of falling rock trajectories near existing protective measures, new protective measures are installed along the collision lines between the falling rocks and the slopes. The interception rate is increased to greater than 95%, and the probability of falling rock impacting the plant is reduced to less than 5%. The results show that the role of the protective net is very significant.

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