Characteristics analysis of the reservoir landslides base on unmanned aerial vehicle (UAV) scanning technology at the Maoergai Hydropower Station, Southwest China

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Abstract. With the development of unmanned aerial vehicle (UAV) technology, UAV scanning technology has been applied widely in the world. However, the application of UAV is not sufficient in the current geotechnical engineering due to its high cost. The paper analyzed landslide characteristics of the Maoergai reservoir base on a small UAV. With the help of Pix4D, the image data collected by UAV can be processed into a three-dimensional terrain. And then the characteristics including landslide scale, landslide elevation, average slope can be obtained by use of Google Earth software. Analysis results reveal that the occurrence frequency of landslides is very high, and the most prone to triggering reservoir landslide elevation is about 2150m~2199m. In addition, 30° to 35° is the major slope range that reservoir landslides occurred. Water fluctuation (rising or drawdown of the water level) played a key role in triggering Maoergai reservoir landslides. The potential initiation mechanism of a reservoir landslide due to the fluctuation of water level was discussed in the paper. Through the application in the hydropower engineering, the paper provided some ideas for the further development of UAV scanning technology.

1. Introduction

After several decades of development, the performance of UAV has been improved and its manipulability is getting better [1]. Especially with the rapid development of computer, communication, navigation, and other technologies, UAV technology has begun to develop from the research stage to the practical stage rapidly [2]. At present, UAV has been widely used in various fields, especially in the field of remote sensing surveying and mapping. For example, in 2003, the first large-scale use of UAV technology obtained the remote sensing data of more than 600,000 square kilometers, Weihai city, China. In addition, the UAV played an important role in the earthquake zone including the Wenchuan Earthquake (2008), Lushan Earthquake (2013) and Jiuzhaigou Earthquake (2017), China, which easily gained the valuable information of those unreachable areas and provided a favorable basis for rescue and disaster assessment. However, many applications of UAV are limited to photographing scenes or acquiring videos at present, which lack the deep processing application for acquisition images [3].

Reservoir-induced slope failure is a major problem in water conservancy and hydropower projects. But people didn't play real attention to these problem until happening Italy Vaiont landslide accident.
which caused significant casualties [4, 5]. There are reservoir bank stability problems in most of hydropower stations in China, such as the Three Gorge project, Yangtze River, Ertan hydropower station, Yalong River, the Lijiaxia Hydroelectric Project, Yellow River, etc. Construction of The Three Gorge project as the world's largest water conservancy project started in 1994 [6, 7, 8], but the length of its reservoir bank is more than 5927 km in which reservoir landslides are the most serious problem. Especially human beings pursue a higher cost performance (less reservoir inundation area, less resettlement, bigger storage capacity, larger capacity) in the construction of hydropower projects [8], the stability of reservoir slope becomes more serious. Therefore, the paper focuses on the problem of slope failures of a hydropower reservoir in China southwest mountainous area.

According to the previous studies [2, 3], UAV remote sensing data is better than the open data of Google Earth software significantly, more accurate three-dimensional map can be obtained using UAV scanning technology[9, 10]. The paper treated the Maoergai reservoir as a special example of reservoir landslides, in which the mountains are mainly composed of slates, phyllite, sandstone. When the rock and soil encounter water, these soluble cements are easy to react with water that will lead to lost connectivity between rock particles. That means the water can cause great effect on the physical and mechanical properties of the Zigong argillaceous siltstone. Therefore, the fluctuation of reservoir water level caused a large number of slope failures. With the help of a small UAV, landslide characteristics of the Maoergai reservoir were analyzed including landslide scale, landslide elevation, and average slope. By studying the relevant data of landslide failure in the reservoir area, the main causes of slope instability were found, and some corresponding control measures can be taken. In the paper, a new technology was carried out to study reservoir landslides using some software, some useful conclusions are presented.

2. UAV scanning technology

The paper selected UAV aerial survey, Pix4Dmapper and Google Earth software as the main technical means to study the landslide characteristics of Maoergai reservoir.

2.1. UAV flight system

UAV remote sensing technology has many advantages: long duration, high-risk area detection, unconstrained terrain and climate, low cost, high resolution, and others [1, 2, 3, 7], which has been widely used at home and abroad. Using UAV can not only obtain remote sensing images using its high-resolution camera, but also achieve image automatic shooting and acquisition via air and ground control equipment. In the world, there are multipurpose UAV, and these battery life ranges from a few minutes to a few hours.

In the paper, a vertical landing and fixed wing UVA(CW-10) was used, and its battery life was more than 60 minutes, as shown in Figure 1(a). Using easy-to-control flight control software (Figure 1(b)), the above mentioned UAV can obtain real-time scanning of the target area.

![Figure 1](image.png)

**Figure 1.** UAV flight system: (a) UAV and signal booster, and (b) ground station for UAV.
According to Figure 1, the ground station of CW-10 mainly consists of remote control, computer, video display, power system, radio station, flight control software and other equipment. The UAV is mainly used for aerial surveying and mapping, pipeline inspection, emergency, geological survey and others. And the major technical indexes of CW-10 are shown in Table 1.

| WINGSpan (m) | Battery life (minutes) | Fuselage length (m) | Maximum speed (m/s) | Maximum take-off weight (kg) | Cruising speed (m/s) | Payload (kg) |
|-------------|------------------------|---------------------|---------------------|------------------------------|----------------------|-------------|
| 2.6         | 60~90                  | 1.6                 | 30                  | 12                           | 20                   | 1~2         |

As shown in Table 1, the UAV has a wingspan of 2.6 meters, and its fuselage is 1.6 meters. In addition, it can continue to fly for more than 1 hour. Although its normal cruising speed is 20 meters per second, its maximum speed can reach 30 meters per second. The CW-10 can carry up to a 1~2 kilograms’ payload, and its maximum take-off weight is 12 kilograms.

### 2.2. Aerial image processing software

Aerial image data often needs to be converted into terrain information using some techniques, and there are many processing software to realize this process, for example Smart3D, Pix4Dmapper, PhotoScan, and others. In the paper, Pix4Dmapper was selected to deal with aerial images of CW-10, as shown in Figure 2(a). The software can't only realize automatic processing image data, but also automatically calculate the external orientation information of the basic images in the three-dimensional space. In addition, the accuracy of 3D topographical map will be higher by adding ground control points. The operational process to 3D terrain data of the software is shown in Figure 2(b).

**Figure 2.** The software of Pix4Dmapper: (a) software initial interface, and (b) operation process.
As shown in Figure 2, aerial images can be converted into KML files through Pix4Dmapper software processing. And then the KML data can be analyzed using Google Earth software.

2.3. Analyzing topographic map data
Although Google Earth software has convenient measurement functions including measuring distance, area, and volume, the accuracy of itself terrain photo data is very poor and not timeliness [2, 7, 11]. Therefore, the terrain photo data of Google Earth software is difficult to be used directly. UAV technology can be used to obtain the latest terrain data of specific regions, considering that many works require the latest and accurate topographical map. And it has been proved that the error of 3D terrain data established by aerial photography is about 10cm [7]. The remote sensing data obtained by UAV flight can replace the outdated and fuzzy satellite map of Google earth software so as to analyzing its topography and landslide disaster accurately, as shown in Figure 3.

![Remote sensing data of UAV](image)

**Figure 3.** The software of Pix4Dmapper: (a) software initial interface, and (b) operation process.

According to Figure 3, the Google Earth can analyze its length, area and volume of the target area by using of the KML file obtained by Pix4Dmapper software.

3. Maoergai reservoir and Aerial photography
Reservoir landslide is a major problem in water conservancy and hydropower projects, especially in China [11, 12, 13]. The paper analyzed slope failure problem of Maoergai hydropower reservoir in China southwest mountainous area by means of UAV technology.

3.1. Maoergai reservoir landslides
The Maoergai Hydropower Station is located at the middle reach of the Heishui River, Heishui County, Aba Autonomous Region of Zang and Qiang Race in the sichuan Province, southeast China (as shown in Figure 4(a)). And it is the third hydropower station for cascade development of the Heishui River with the capacity of controlling water level by year with the dam height of 147m. Its normal water level is 2133m, and the storage capacity corresponding to the normal water level is $5.35 \times 10^8$ m$^3$. Figure 4(b) shows the reservoir landslides of the Maoergai Hydropower Station.
As shown in Figure 4, the study area is belong to the mountainous area, the slope is steep and strongly cutted by river water. In addition, vegetation is not well developed at the topper mountain, so that the shallow rock masses are strong weathered due to long term geological effect. Field investigation results show that the average slope of the reservoir mountain is range from 30º to 60 º, and abundant deposits are existed at the lower slope.

Furthermore, the stratum lithology is very complex in this area, mainly include aeolian deposit loess of Quaternary, residual diluvial soil and gravelly soil from old landslide, and the main type of rock masses are consists of sandy phyllite with a little carbon phyllite, which would be easily softened when soaking in water.

![Figure 4. Site location of the Maoergai Hydropower Station: (a) location of the Maoergai reservoir, and (b) landslide conditions of the Maoergai reservoir.](image)

According to Figure 4(b), different scales of landslides are well distributed along the both banks of the reservoir based on long-term monitoring. These landslides are formed in different time and related with the history of the reservoir water level fluctuation. Most of the reservoir landslides are near to the water surfaceline with small volume, and happened in the shallow and deep reservoir landslides during the operation process of the Maoergai Hydropower Station.

### 3.2. Aerial photography

The disaster of reservoir landslides is very serious including shallow sliding and deep sliding, and the reservoir landslides are mainly located in the left reservoir, as shown in Figure 4(b). In the paper, the left reservoir was selected as the target area for aerial photography and the landslide characteristics were analyzed by use of Google Earth software. The three-dimensional topographic map of the left reservoir was obtained by processing aerial images including the digital orthophoto map (DOM) and the digital elevation model (DEM), as shown in Figure 5.

![Figure 5. The three-dimensional terrain of the Maoergai reservoir: (a) the digital orthophoto map (DOM), and (b) the digital elevation model (DEM).](image)
With the help of Pix4Dmapper, DOM can be imported into Google Earth using KML file. Google Earth can analyze the length, area and volume of the landslides in the left reservoir base on Figure 5.

4. Statistical results analysis of the reservoir landslides
According to the mentioned above, the landslides of the left reservoir can be analyzed by UAV aerial photography. Figure 6 shows the distribution of the reservoir landslides.

![Figure 6. The distribution diagram of the reservoir landslides from the left reservoir.](image)

Table 2. The statistical results of the left reservoir landslides for UAV aerial photography.

| Landslides | Length a (m) | Length b (m) | Area (m²) | Volume (m³) | Relative height (m) | Mean slope (°) |
|------------|--------------|--------------|-----------|-------------|---------------------|---------------|
| 1          | 227          | 104          | 16008     | 190125      | 148                 | 33            |
| 2          | 155          | 62           | 7256      | 35509       | 98                  | 32            |
| 3          | 49           | 52           | 1340      | 2037        | 32                  | 33            |
| 4          | 202          | 134          | 15416     | 62611       | 127                 | 33            |
| 5          | 221          | 145          | 20697     | 48190       | 114                 | 31            |
| 6          | 183          | 141          | 13095     | 27322       | 117                 | 33            |
| 7          | 95           | 76           | 5219      | 32760       | 56                   | 30            |
| 8          | 118          | 50           | 5535      | 9651        | 75                   | 35            |
| 9          | 131          | 65           | 5422      | 26350       | 89                   | 34            |
| 10         | 333          | 295          | 66633     | 15783       | 182                  | 32            |
| 11         | 68           | 71           | 2424      | 597506      | 43                   | 33            |
| 12         | 90           | 109          | 5992      | 8012        | 57                   | 30            |
| 13         | 165          | 158          | 17243     | 10773       | 85                   | 27            |
| 14         | 57           | 68           | 2188      | 77010       | 35                   | 31            |
| 15         | 87           | 51           | 2774      | 4072        | 56                   | 29            |
| 16         | 84           | 92           | 4648      | 5656        | 50                   | 31            |
| 17         | 224          | 150          | 23843     | 18217       | 141                  | 32            |
| 18         | 102          | 43           | 3982      | 79101       | 63                   | 31            |
| 19         | 112          | 86           | 8261      | 13965       | 65                   | 30            |
| 20         | 293          | 144          | 25690     | 38177       | 171                  | 31            |
| 21         | 358          | 200          | 42495     | 405840      | 219                  | 31            |
| 22         | 333          | 184          | 41999     | 325507      | 201                  | 32            |
| 23         | 357          | 184          | 52380     | 188605      | 221                  | 31            |
| 24         | 103          | 101          | 7185      | 172012      | 59                   | 29            |
| 25         | 153          | 98           | 10016     | 20271       | 92                   | 31            |
In the paper, a total of 25 typical landslides were analyzed by studying 3D terrain of the left reservoir. Finally, all landslide characteristics of the left reservoir were recorded carefully using the Google Earth software, and the statistical results were shown in Table 2.

As shown in Table 2, the sizes of landslides were calculated including landslide scale (area and volume), landslide elevation, and average slope. Next, these landslide data were analyzed systematically.

### 4.1. Landslide scale

Field investigations and observations show that different scales of landslides are well distributed along both banks of the left reservoir. These landslides are formed in different time and related with the history of the reservoir water level fluctuation. According to Table 2, The statistical results of landslide area and volume were shown in Figure 7.

![Figure 7](image)

**Figure 7.** Landslide scales of the left reservoir: (a) landslide area; (b) landslide volume.

As shown in Figure 7(a), there are 23 landslides that these areas are less than 50000 m² with 92% percent for the left reservoir landslides; For landslide volume (Figure 7(b)), the volume between 10000 to 50000 m³ has the highest proportion, up to 44%. Almost all the landslides are less than 500000 m³, and the largest landslide volume is 597506 m³. According to slope classification specification [14], most of these statistical landslides belong to small-scale landslides but the biggest landslide reaches the size of medium-scale landslide.

Although the hydropower reservoir has not yet triggered the large-scale landslide disaster base on the statistical data, small-scale landslides continue to occur with great frequency. This situation could affect reservoir and dam safety, therefore it is necessary to put forward some corresponding preventing and controlling measures. In a word, statistical results show that Maoergai reservoir should be taken timely measures to protect reservoir landslides.

### 4.2. Landslide elevation and average slope

The reservoir water level elevation was about 2100 m base on the monitoring data of UAV, so the relative height of reservoir landslides was equal to the difference between slope trailing edge and reservoir water level. As shown in Figure 8(a), reservoir landslide number was calculated with an interval value 50m respectively. In addition, landslide number was also recorded with an interval value 3º base on mean slope angle respectively (Figure 8(b)).

According to Figure 8(a), the landslides of the left reservoir were distributed in different elevation, and the number of landslides between 50 m and 99 m was high especially, up to about 48% of all statistical landslides. Besides, the relative height of all landslide was under 249 m. Therefore, it can be concluded that Maoergai reservoir landslides are mainly distributed between 2100m to 2349m, which is the dominant height in triggering landslides.
In addition, the factor of occurring landslides is closely related with slope gradient and geomorphology type. Therefore, it is meaningful to analyze the mean slope of reservoir landslides. As shown in Figure 8(b), the reservoir landslide with the mean slope between $30^\circ$ and $32^\circ$ was the largest, and the amount of this range was 15 landslides, up to 60%. According to the perspective of landslide development, there were 22 landslides ranging from $30^\circ$ to $35^\circ$, which was the dominant mean slope in triggering reservoir landslides. Besides, all reservoir landslides are almost developed on the steep slope, so the topography of Maoergai reservoir landslides is mainly prone to the steep slope.

5. Discussion
As shown in Figure 4(b) and Figure 6, most of the reservoir landslides are neared to the water surfaceline with small volume, and happened in the shallow deposits, but there are little number of reservoir landslides happened in the deep rock masses with large volume. According to the statistical results of UAV, the lower slope in the reservoir area are immersed after reservoir impoundment. The shear strength of the rock and soil materials were decreased due to the long term of water softening effect [15]. And reservoir water level was continuously changed due to the operation of hydropower station. Therefore, reservoir landslides with different scales were happened at different time and locations, which was closely related with the history of water reservoir level fluctuation[16].

In the study area, the reservoir slopes are steep, and the shallow slope rock masses are fractured, and widespread loose deposits are accumulated at the lower slope and immerged in the water. These favorable geological conditions provide the susceptibility of the reservoir landslides. In addition, reservoir water can change slope physical and mechanical properties and reduce the shear strength of rock and soil mass. The reduction of shear strength can bring some hidden dangers to the stability of reservoir landslides [16, 17]. Water fluctuation (rising or drawdown of the water level) often play a key role in triggering reservoir landslides[18]. The water level rising and falling can also increase the weight of landslides and reduce the shear strength of rock and soil mass (as shown in Figure 9).

According to Figure 9, bank slope submerged parts can form buoyancy effect, thus it can reduce effective gravity. Especially for rapid drawdown of reservoir water level, the descending speed of slope internal saturation line isoften far lagging behind the drop speed of slope outsiderswater level, which can lead to the internal slope with high pore pressure and forming the seepage force toward the free face. This situation will accelerate the slope failure process. Small failures at the toe of reservoir slope do not have a great impact on the reservoir, but a free surface will form for the upper large volume of slope soils. Finally, the case is possible to plays a key role in some catastrophic reservoir landslide. With the raise of water level, major adverse effect on the bank slope include the fact that more slope soils are saturated by water, which causes shear strength to decrease, as well as seepage-induced pore pressure in the slope. These two aspects will decrease the stability of the bank slope as the water level rises.
Figure 9. Potential initiation mechanism of a reservoir landslide due to the fluctuation of water level.

6. Conclusions
According to the above mentioned, the proposed method analysed reservoir landslide characteristics of a hydropower station by use of unmanned aerial photography technology. Combining with Pix4Dmapper and Google Earth software, the presented technology obtained the data including landslide scale, landslide elevation, and average slope. In the paper, a new technology was carried out to study reservoir landslides using a few software, some useful conclusions were gained as following.

(a) By analyzing the UAV scanning technology, it can be used to analyze the triggering mechanism of reservoir landslide, contributing to treating landslides.

(b) For reservoir landslide scale, these areas of 92% percent landslides are less than 50000 m$^2$, and the volume between 10000 to 50000 m$^3$ has the highest proportion, up to 44%. Almost all the landslides are less than 500000 m$^3$ belonging to small-scale landslides, and the largest landslide volume is 597 506 m$^3$ belonging to medium-scale landslides.

(c) For reservoir landslide elevation and average slope, the elevation between 2100m to 2349m is the dominant height in triggering landslides, which is the main elevation range needing slope disaster prediction and slope control. 30º to 35º is the dominant average slope in triggering reservoir landslides of Maoergai Hydropower Station, and its micro-topography is mainly prone to the steep slope.

(d) According to the statistical results of UAV, the reservoir landslides with different scales were happened at different time and locations, which was closely related with the history of water reservoir level fluctuation. The favorable geological conditions and reservoir water level fluctuation are the two most important factors affecting slope stability for Maoergai reservoir.

By analyzing the reservoir landslides, the statistical results show good accuracy and efficiency of the proposed method with maximum error of 20cm, which has high reference value for the requirement of landslide data statistics. The most important conclusion drawn from the study is that UAV scanning technology is a good way to deal with geological investigation and analysis.

Competing Interests
The authors declare that there is no conflict of interests regarding the publication of this paper.

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