Research on Oblique Aerial Photography and its Application in Detection of Hidden Geological Hazards

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Abstract: The Wu Gorge section of the Three Gorges Reservoir is prone to landslides and collapses of rock masses, which poses considerable threats to the transportation safety along the watercourse of Yangtze River. The oblique aerial photography technique can accurately present the profile and texture information of the observed objects, which can provide data for early detection of geological hazards. In this study, the technique of oblique aerial photography was analyzed in depth, and the obtained oblique aerial photographs were combined with the position and orientation system (POS) data and the ground control points to build a three-dimensional model, and a geological disaster evaluation model was built based on such factors as geological conditions, landform, and hydrological conditions for geological hazard evaluation. Meanwhile, indoor interpretation and fieldwork surveys were performed to summarize the patterns of development and distribution of geological disasters, identify the major contributors to geological disasters in the study area, and master the characteristics of liability of the study area to geological disasters and hidden hazards.

1. Introduction

The construction of the Three Gorges Dam and the accompanied population migration have led to changes in the local geological environment [1,2]. Specifically, the original geological formations featured by considerable differences in the landform and topological cutting effects have changed into formations prone to such geological disasters as landslides, collapses and mudslides [3]. The Wu Gorge section, after storing water, has seen the occurrence of Wang Gorge landslide, Gongjiafang landslide, Hongyanzi landslides, etc. To identify the hidden geological hazards that may threaten safety of the watercourse and comprehensively evaluate the effect of disaster treatment, it is necessary to perform high-precision aerial remote sensing photographic surveying in the first-level inclined zone, to provide fundamental geographic information for early detection of hidden geological hazards in the Three Gorges Reservoir [4, 5].

The mountains along the banks of Yangtze River are famous for its steepness, strong cutting effects and large altitude differences. Conventional aerial remote sensing technologies are fulfilled by vertical photography with central projections, which are hard to observe the profile information of the ground objects. Though there is some profile texture information along the boundary of the images, the deformation problem is so serious that the images cannot be used. Moreover, the Three Gorges are
subject to the subtropical climate featured by frequent rain storms, which add to challenges and safety risks of fieldwork. The oblique aerial photography technique that emerged in these years can obtain digital images of ground objects from both vertical and oblique angles, and capture texture information both on the top and the profiles; when it was combined with the inertial navigation system, it could obtain high-accuracy location and attitude information. All the obtained images, after data processing, can be integrated into a consistent coordinate system and generate a 3D realistic model [6, 7], which overcomes the technical shortcomings of conventional aerial remote-sensing technologies and geological survey techniques, thereby providing a technical solution to precise aerial remote-sensing geological surveys.

2. Oblique aerial photography

2.1 Technical overview

Oblique aerial photography was first used in the military field such as border monitoring. With the development of computer technology and airborne POS technology, oblique aerial photography become a hot research topic in international remote-sensing surveying. In the technology, some sensors of relative locations are deployed on an aircraft to collect images from vertical and oblique angles, and thus to obtain more complete and accurate information of the ground objects. Vertical aerial photography and oblique aerial photography, combined with the inertial navigation system, can obtain high-precision information of locations and attitudes. The obtained images can be input into a consistent coordinate system by professional image matching and 3D modeling software, and are then distributed online so that users can view and survey online the images from different angles. In 1993, Pictometry, an American company, innovatively a 1-vertical and 4-oblique non-metric cameras to build a “Maltese Cross” structure, which laid a foundation for research and development of oblique photography systems. Later, many oblique aerial remote-sensing devices came into being globally, among which the typical ones were the Penta-Gigicam system by IGI in Germany, the RCD30 produced by Leica [8], the A3 system by Israel [9], and Microsoft’s UCO system. In early 2010, Peacemap introduced the oblique photography measurement system form Pictometry, which marked the start of research on oblique photography measurement in China. In October 2010, the team of Academician Liu Xianlin developed the first oblique camera in China SWDC-5, and successfully applied it to the oblique photography project in Changchun [10], after which following the steps were the AMC5150 system developed by Shanghai Hangyao, and the TOPDC-5 system developed by China TOPRS Technology. The popular “1+4” sensor system is the system consisting of one vertical sensor and four oblique sensors. With technological progress, oblique photography devices capable of carrying more oblique cameras emerge. Table 1 shows the parameters of the mainstream oblique aerial photography devices on the market. After completing capturing of oblique aerial images, the images need to be processed, that is, the aerial images should be calculated and pre-processed, to build a 3D model that reflects the real-world scenes. The currently available automatic moulding software includes the Pictometry system, the Street Factory system. The Agisoft Metashape system. The Pix4D mapper system, the Context Capture system, the Photomesh system, as well as some Chinese software like the Mirage3D system by CH-NB, the DP-Smart system by Wuhan Tianjihang Co., Ltd., and the Wit3D system by Wuweet Technology.

| Title          | Focus/mm (vertical/oblique) | Pixel/μ | Image size Vertical/oblique | Camera combination | Manufacturer |
|----------------|----------------------------|---------|----------------------------|--------------------|--------------|
| Penta-DigiCam  | 50/80                      | 3.76    | 6716×8964                  | 1+4                | IGI          |
| AOS            | 47                         | 6.8     | 7228×5428                  | 1+2                | Trimble      |
| RCD30          | 50/50                      | 5.2     | 10320×7752                 | 1+2 or 1+4        | Leica        |
| A3             | 300                        | 7.4     | 4864×3232                  | Single-lens whiskbroom | VisionMap        |
| UCO            | 51 (panchromatic), 25.5 (RGBN)*/80 | 6.0 (panchromatic), 5.2 (RGBN)/5.2 | 11674×7514 (panchromatic), 6735×4335 (RGBN)/13450×4520 (post-slicing) | 4+6 | Microsoft Vexcel |
| AMC5150        | 80/110                     | 4.6     | 11608×8708                 | 1+4                | Shanghai Yaohang |

Table 1 Technical parameters of major oblique aerial photography equipment
2.2 Key technologies

1) Simultaneous adjustment of multi-view images

Conventional aerial photography methods are based on the classical theories of collinearity equations of vertical images, but oblique photographs contain oblique photos that are shot at given angles with the ground. Thus, in simultaneous adjustment of multi-view images, the geometric and overlapping relations between images were explored, and the airborne positioning and attitude-identifying system was used to provide six elements of exterior orientation; meanwhile, an increasingly precise iterative matching strategy was used to fulfill image matching and free net adjustments, and the united computation results were based to assess the precision of the adjustment results.

2) Multi-view image matching

The multi-view images obtained by oblique aerial photography feature wide coverage, high resolution and high overlapping degrees, but they suffer some shortcomings like serious geometric deformation, high similarity of features of ground objects, occlusion of images from different angles, massive data and redundancies, which makes it difficult for conventional grey matching algorithms to meet the needs of image matching. To improve the accuracy and efficiency of multi-view image matching, researchers globally have probed deep and made great achievements. For instance, the geometric constraint method proposed by Zhang et al. [11], the least square method by Ji et al. [12], the self-adaptive window strategy proposed by Dai et al. [13], the facet-vector method by Furukawa et al. [14], which all achieved reliable, efficient and dense matching effects of multi-view images.

3) Digital surface model production

The digital surface model (DSM) refers to the elevation model that reflects the elevation of natural and artificial objects on the ground surface (such as buildings and trees). The DSM which can fully reflect the undulation features of the ground objects is an important part of modern basic spatial data and also a major achievement of dense matching of multi-view images by oblique aerial photography. However, due to the different angles of observation of the ground objects and the undulation of the ground surface, the differences in the plotting scale and ground surface resolution between the oblique images, the DSM production based on oblique images is more challenging than conventional methods. One solution is to assign corresponding image units to the six elements of exterior orientation calculated by aerial trigonometric surveys, and then perform pixel-level feature matching and precise dense matching; when the data are massive, the parallel algorithm is introduced to obtain high-density DSM initial results, and the thresholds are set as required to perform filtering; at last, the matching units were inserted and merged to produce the DSM.

4) True digital ortho map

True digital ortho map (TDOM) refers to the technique of correcting the geometric deformations by numerical differentiation method based on the obtained DSM data. TDOM re-samples the images of the whole section, and the quality of the re-sampled images relies on the quality of the DSM. In other words, only a high-quality DSM can produce high-quality true digital ortho maps [15]. One challenge in TDOM of oblique aerial photography is that it involves matching of ground objects and multi-view images of a massive object space and image space, which is data-intensive and computation-intensive. In this step, the object space and image space can be processed simultaneously, i.e., with the DSM result as the basis, the geometric feature vectors can be used to extract the semantic information of the landform and ground objects, and meanwhile such operations as segmentation, clustering, and edge extraction are performed on the multi-view images to extract semantic information from the image space. Then, the results of united adjustments and dense matching are used to find the sites of the same name in the object space and the image space to fulfill united correction that takes into account the geometric radiation features [16]. After that, the light and color of the results are averaged to obtain the true digital ortho maps.
2.3 Technical advantages of oblique aerial photography

1) The technology can reflect the features of landform and ground objects in a more authentic way. It allows the users to observe the ground objects from multiple angles, and the real-scene 3D imaging results include the profile and texture of the ground objects, which reflect the actual conditions of the objects and make up the shortcomings of vertical aerial photography. The concept of digital twin that originates from oblique photography has vividly interpreted the portraying effect of the observed objects by 3D models.

2) Oblique aerial photography can perform all-round quantitative and qualitative analysis. The DSM, TDOM and 3D models obtained by oblique aerial photography can, with the support of software platforms, can directly measure the altitude, length, area, angle, slope and earth volume, which expanded the application fields of the oblique aerial photography technology.

3) Images obtained by the oblique aerial photography can be easily released or shared online. The outcomes of the oblique aerial photography have diverse forms and can be defined as required by the users, which meets the needs of different ports for cloud storage and computation, and has good scalability and potential for secondary development.

2.4 Development directions

Having developed for about three decades, the oblique aerial photography technology has solved many technical challenges in hardware and software research and development as well as application, and realized automation of data collection and imaging. In the future, we need to explore how to minimize the size of the device, combine the technology with multispectral, hyperspectral and laser radar techniques to integrate multi-source data so as to tackle technical problems like loss or distortion of images on 3D models or unsatisfactory matching results.

3. Technical workflow

Figure 1 shows the technical workflow of the oblique aerial photography technology.

![Figure 1](image-url)
three line elements \(x\), \(y\), and \(z\) of the location at the time of exposure, as well as the three angle elements \(\phi\), \(\omega\), and \(\kappa\) captured by the attitude system at the time of exposure. To meet the standards for the precision of the final images and application, other data from the ground stations and the satellites should also be collected.

2) Data pre-processing. When the airborne and ground object data are captured, all the data, including the flight quality, the image quality and the data quality are checked, and the data that fail to meet the standards are remedied till the quality of all data reach the standards. Then, for each image, the colors and the contrast are adjusted to reach an equilibrium and make the images fully reflect the details of the ground objects. After that, the airborne POS data are processed, and the elements of exterior orientation that meet the accuracy requirements are taken as the weighting values assigned to each oblique image, so that the images have the position and attitude in the 3D space. At last, the ground control sites are combined with aerial triangulation so that each pixel on the oblique images shows the location information in the prescribed coordinate framework.

3) Production of the oblique model. The model production can be divided by the results into monomeric model production and non-monomeric model production. The former directly projects the existing 3D line-frame model into a 3D model through texture projection. The model obtained by this technique can delete, modify and replace monomeric ground objects, which is applicable to regions featured by frequent changes of ground objects. The non-monomeric model data production adopts a fully automatic production method, in which the multi-view images, after geometric correction and adjustments, can produce high-density point clouds, and irregular triangle networks can be generated based on the cloud to produce a texture information 3D model. This method features a short cycle, cost efficiency and accuracy at the surveying level.

4. Application scenarios

4.1 Geological background of the surveyed area

The objectives of this geological survey are to obtain high-accuracy aerial remote-sensing data and landform parameters of a disaster-prone region by the oblique aerial photography technology, collect aerial remote-sensing data of the geological problems like landslides, collapses and subsides along the banks of Three Gorges Reservoir, analyze the hydro-fluctuation belt in the surveyed region, and identify geological hazards and environmental problems in the surveyed area so as to facilitate monitoring, prevention of geological disasters and geological protection. Wu Gorge, the surveyed area, is located at the intersection of the arc formation of Bashan Mountain, the belt of folded strata in eastern Sichuan, and the faulted upfolding area along the boundaries of Sichuan, Hubei, Hunan and Guizhou. The Yangtze River stretches from the west to the east, and seven branches including Daning River and Baolong River present strong cutting effects from north to south. The area is dominated by deep valleys and medium- and low-altitude mountains, with large fluctuations and slopes. The elevation of the valley bottom is within 300 m, and the elevation at the top of the bank is above 1000 m [17]. The exposed strata in the study area are sedimentary strata and some sporadic quaternary strata; besides, the secondary folded strata and fracture strata have fully developed, with undulating surfaces, deep valleys, and complicated landforms. As previous data show, the area is subject to the effects of strata development, formations, hydrological and human factors, and is prone to geological disasters like landslides, dangerous rocks, mudslides and collapses that are have wide coverage and diversified forms.

4.2 Hardware and software

Table 2 shows the hardware and software used in the oblique aerial photography project.

| Hardware                  | Model          | Software platform | Title         |
|---------------------------|----------------|-------------------|---------------|
| Flight platform           | PC6 single-engine aircraft | Flight line design | IANS         |
| Oblique aerial camera     | AMC5100        | Image processing  | Capture One   |
| Stable vehicle            | GSM4000        | POS data processing| POSPac MMS    |
| POS system                | APPLANIX AP20  | 3D modeling       | Context Capture|

Table 2 The software and hardware of this project
4.3 Result accuracy
Nine aircrafts were employed to shoot oblique aerial photographs for over forty hours, and a total of 34,715 photos were obtained, covering an area of 120 km$^2$, the maximum ground surface resolution at 0.06 m, and the minimum resolution of 0.19 m, and the survey strictly followed the relevant standards [19-20]. In terms of the flight quality, the flight curvature was below 0.87%, and the inclination of the vertical images is below 6°, the maximum and minimum flight overlapping and vertical overlapping rates are 84% and 78%, respectively, the spiral deflection angle is controlled within 5°, and the flight height of the same aircraft remains within 50 m. In terms of the quality of the images, the images have rich texture, proper contracts, gentle tones, and a high resolution that allows observation of details of ground objects. The data are processed by POS data pretreatment, and the result shows that the data have complete exposure, correct flight trajectories, and accuracy of position and attitude that meets the standards of corresponding plotting scales. Meanwhile, based on the 63 ground stations are employed, the airborne POS-assisted air triangulation measurements of oblique aerial photographs are performed. The results are compared with 30 accuracy rates and the errors are calculated. The calculation results reveal that the images conform to the high land accuracy standards with a plotting scale of 1: 2000. Figure 2 shows the outcome of the real-scene 3D model of oblique aerial photography.

![Real-scene 3D model of the city](image1)
![Real-scene 3D model of the landslide](image2)

Figure 2 3D model of oblique aerial photography

4.4 Geological disaster survey
The aerial remote-sensing data obtained by high-accuracy oblique aerial photography were taken as the major source of data, and the high-resolution satellite remote-sensing data were used as auxiliary data; the data of geological disaster remote-sensing surveys obtained from the Three Gorge Reservoir in 2003 and 2009 by the China Aero Geophysical Survey and Remote Sensing Center for Natural Resources were used as the basic data, to establish the interpretation system for remote-sensing data of geological disasters, which can interpret the geological disasters like landslides, collapses and mudslides in Three Gorge Reservoir, and hence measure and assess the monomeric features of geological disasters. Specifically, the features of the ancient (old) landslides, fractures, the ripping grooves, the front-edge elliptical hills, vegetation, water systems and geological disasters are extracted, the geological disaster remote-sensing survey of the first-level slope unit based on the surface hydrological features of the DEM was performed to analyze the development and spatial distribution characteristics of geological disasters in the study area. Meanwhile, based on previous research results, such evaluation factors as the slope, the slope orientation, the rock strata features, the geological formation, the slope types, the water system, and human activities were selected, and with the theoretical foundation of the information volume model analysis method (the Bayesian probability model) and with the slope unit as the evaluation unit, a geological susceptibility evaluation model was established to assess the susceptibility of the slope unit to geological disasters. With the research methods mentioned above, and the results of indoor analysis and outdoor fieldwork, the following findings were obtained.
1) In the study area, there were 308 developing geological disasters, 150 dangerous rock masses, 14 dangerous rock belts, 11 development regions of abrupt cliffs, and 9 sections of strong deformations underwater, 4 regions of potential geological hazards under human activities. The distribution pattern of geological hazards in the Wu Gorge region of Three Gorges Reservoir.

2) The geological and environment problems, the formation patterns of typical dangerous rock masses, and potential geological hazards in the study area were understood and re-divided, which would provide reliable data for prevention of potential geological hazards in the Wu Gorge area in Three Gorges Reservoir. The major geological problems in the study area included deterioration of the bed rocks in the hydro-fluctuation belt, the collapse of steep valleys, the consequent air-bound dangerous rocks, hidden geological disaster risks, sediment accumulation at the estuary, and human activity-induced geological damages. There were eight major development patterns of dangerous rocks, including the tower-type dangerous rocks, the plate-type dangerous rocks, the cataclasite, the cavity-type dangerous rocks, the fractured dangerous rocks, the corroded rocks, the eroded rocks, and complex rocks.

3) The results of the survey on the local hidden geological hazards showed that the distribution of potential geological hazards is substantially affected by the geological conditions, and the geological hazards feature concentrated distribution: 11 areas are disaster intensive, including the belt from Gongjiafang to Dulong, from Shizhuzi to Jianping Village, from Hengshixi to Wangxia Village, stretching 43.5 km, and the disaster susceptibility level is high, and the areas of high- and medium-level susceptibility present a dumbbell-shaped distribution pattern. The regions of these two types of susceptibility have similar areas of coverage, taking up 36.94% and 41.25% of the whole region respectively, and the low-susceptibility region is only 21.81% of the study area, which poses great threats to the life of local residents and ships that pass this area.

5. Conclusions and suggestions
To meet the needs of aerial remote-sensing investigations of geological disasters in Three Gorges Reservoir, the airborne POS-assisted oblique aerial photography technique is employed to obtain high-resolution aerial images that reflect the profile and texture information of the Wu Gorge section and the elements of exterior orientation that meet the accuracy standards of 3D modelling. The ground control points are combined for the 3D model production, which has such features as high resolution, multi-views and measurability. Meanwhile, the previous research achievements and satellite images are collected, and based on the formation principles of geological disasters like the landslides, collapses, mudslides, and subsides, the deformation areas of the hydro-fluctuation belt in the Reservoir are partitioned, and the spatial distribution features, influencing factors and risk levels of of key disaster areas and geological disaster-intensive areas caused by human activities are analyzed. It provides high-precision geological data for geological disaster prevention and environment protection as well as technical supports for regional planning, enriches the measures for aerial remote-sensing geological investigations, provides new inspirations for geological investigations of areas of key engineering areas like the Three Gorges Reservoir construction project, and confirms the application potential of oblique aerial photography in geological investigations.

As the oblique aerial photography technology involves many technical details, and in real-world application, the 3D modeling results, due to the massive data volume and fragmentation, suffer from such problems as massive data transfer and slow loading, resulting in large consumption of hardware resources and time overheads. Besides, the model production software is a highly enclosed system, the model production is principally completed automatically, and the results often show problems like unsmooth surface of the water bodies, and suspension of trees. Moreover, as the results of model production are principally non-monomorphic, and the products can only allow browsing but cannot support such functions as attribute editing and themed image production. In the future, construction of databases, standardization of data ports, and secondary development of GIS management platforms can better present the visual effect of the 3D model, and deeply explore the statistical value of 3D modelling results.
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Funding: the project is funded by the project by China Geological Survey (Grant No.: DD20190514).

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