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Postprint of Numerical Aerial Photogrammetry Study on Landslide Disasters in the Meizhou Region

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Abstract

This study proposes a monitoring methodology based on numerical aerial photogrammetry to address the recurrent landslide disasters affecting expressways in the Meizhou region. High-resolution imagery is acquired through UAV-mounted DMC digital cameras and processed via aerial triangulation, orthorectification, and Digital Terrain Model (DTM) reconstruction using the LPS module of ERDAS IMAGINE software, thereby enabling precise analysis of surface deformation in landslide zones. Results demonstrate that this approach efficiently generates orthoimages and DTMs, resolving the issues of low efficiency and high cost associated with traditional monitoring techniques (e.g., total stations, GPS), and provides reliable data support for research into landslide failure mechanisms and intelligent prevention and control.

Full Text

Numerical Aerial Photogrammetry Study on Landslide Disasters in Meizhou Region

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Abstract

This study addresses the frequent occurrence of landslide disasters along expressways in the Meizhou region by proposing a monitoring methodology based on numerical aerial photogrammetry. High-resolution imagery was acquired using a DMC digital camera mounted on an unmanned aerial vehicle (UAV) and processed through ERDAS IMAGINE' s LPS module for aerotriangulation, orthorectification, and digital terrain model (DTM) reconstruction. The results demonstrate that this approach efficiently generates orthophotos and DTMs, overcoming the limitations of traditional methods (e.g., theodolites, GPS) in terms of efficiency and cost, while providing reliable data for landslide mechanism analysis and intelligent disaster prevention.

Keywords: UAV photogrammetry; landslide monitoring; digital terrain model; orthophoto; Meizhou region

Introduction

In recent years, landslide disasters along mountainous expressways have occurred with alarming frequency, posing severe threats to transportation infrastructure safety. Meizhou City in Guangdong Province is located in the eastern mountainous region of the province. Influenced by a subtropical monsoon climate, the area experiences average annual rainfall of up to 1,800 mm. Combined with deeply weathered granite strata and intensive human engineering activities, the landslide risk is notably significant. At approximately 1:57 AM on May 1, 2024, a catastrophic roadbed collapse occurred along the Meizhou-Dapu Expressway (K11+900–K11+950), causing the eastbound half-width embankment to fail. This disaster resulted in 23 vehicles falling, with 52 fatalities and 30 injuries. Historical data reveals that between 2016 and 2022, landslide-induced traffic disruptions on expressways within Meizhou averaged 3.2 incidents annually, with direct economic losses exceeding 50 million yuan (Guangdong Provincial Department of Transportation, 2023).

Geological hazards such as landslides and avalanches are common on slopes worldwide, occurring suddenly and posing significant threats to nearby infrastructure, human lives, and property. Moreover, preventing and responding to these hazards is inherently difficult. As a common structural form, slopes play a crucial role in ensuring the overall stability of complex rock and soil structures. Therefore, slope monitoring is essential for ensuring safety and mitigating risks. With continuous technological advancement, traditional monitoring methods have become inadequate for industry demands, and their limitations have become increasingly apparent. Conventional monitoring methods typically involve manual operation of equipment such as levels, total stations, and GPS, which suffer from low efficiency, high labor intensity, and substantial costs. Consequently, there is a growing consensus within the industry for faster and more efficient slope monitoring solutions.

The development of remote sensing detection technology in recent years has provided powerful tools for topographic and geomorphological research, with successful applications in landslide monitoring including optical satellite imagery, aerial photogrammetry, ground-based photogrammetry, satellite radar interferometry (InSAR), ground-based radar interferometry, airborne laser scanning (LiDAR), and terrestrial laser scanning. Based on these technologies, combined with multi-temporal DEMs, substantial useful information can be extracted to determine displacement magnitudes in specific areas.

Small low-altitude unmanned aerial vehicle (UAV) photogrammetry represents an innovative surveying method renowned for its convenience, speed, efficiency, and high precision. It has been widely applied in engineering construction, disaster prevention and mitigation, and operations, achieving excellent results [4,5,6,7]. An et al. [8] proposed a high-intensity mining ground subsidence monitoring method utilizing UAV-LiDAR technology. Qiu et al. [9] employed UAVs equipped with high-resolution cameras to capture images in a "high-density grid imaging" mode, enabling three-dimensional modeling of study areas for geological survey and risk assessment. Wei et al. [10] summarized and clarified the process of UAV highway aerial data acquisition based on years of practice, providing a theoretical foundation for addressing UAV operational issues. Pi et al. [11] focused on the Tianxi Expressway, the largest transportation hub, employing UAV technology to identify, measure, and analyze three types of high slopes.

Existing UAV slope monitoring analysis methods remain relatively homogeneous, with fewer researchers utilizing photogrammetric methods for slope assessment. This study proposes a monitoring approach based on numerical aerial photogrammetry to address the frequent landslide disasters along expressways in the Meizhou region.

2.1 Photogrammetry

The fundamental concept of photogrammetry is the collinearity equation, which describes the relationship between a target point, the camera's projection center, and the corresponding point on the focal plane along a straight line (Figure 2-1). Using this principle, with known information such as image and camera interior geometry (interior orientation) and camera position and orientation at the moment of exposure (exterior orientation), three-dimensional coordinates can be obtained from stereo image pairs. Light travels in a straight line through the camera lens to the target object, reflects, and is captured by the imaging device. Precise photogrammetric operations require correction of lens distortion, atmospheric refraction, and Earth curvature parameters (Figure 1).

The UAV photogrammetry discussed in this study refers to measurements conducted on UAV photographs. A precision camera mounted on a UAV captures ground images, which are then used for surveying operations to obtain surface point positions and elevations, and to calculate distances between points, object areas, or volumes. Subsequently, planimetric or topographic maps are produced.

Before image acquisition, the flight mission is planned considering several factors: (1) photographic coverage area; (2) photographic scale; (3) camera focal length and image format size; (4) forward overlap; and (5) side overlap [2]. Through overlapping and stitching between images, improved accuracy and precision can be achieved. Images captured along flight strips typically employ 60% forward overlap, while side overlap between adjacent strips ranges from 20% to 30% to form aerial imagery covering larger areas. The flight altitude is assumed constant, with minimal camera tilt angle relative to the vertical direction.

2.2 Interior and Exterior Orientation Parameters

In photogrammetry, the relationship between the camera/sensor, aerial photographs, and ground can be defined using interior orientation parameters, exterior orientation parameters, and ground control points (GCPs).

Parameters that restore the camera’ s light beam geometry at the moment of photography are called interior orientation parameters, which characterize the reconstruction of the camera beam in object space from correct image points. Interior orientation parameters include:

- Principal point coordinates
- Lens focal length
- Fiducial marks
- Lens distortion parameters

For cameras used in aerial photography, lens parameters are determined through laboratory calibration before photography to obtain all parameter values.

Parameters defining the position and attitude of the photograph in space coordinates at the moment of exposure are called exterior orientation parameters. These include:

- Position parameters: X_0, Y_0, Z_0, representing the perspective center’ s position relative to the spatial coordinate system
- Angular parameters: omega (ω), phi (ϕ), kappa ( ), representing two angles of the camera’ s photography direction relative to the spatial coordinate system and one rotation angle of the photograph coordinate axis around the photography axis, collectively called the rotation angle system

2.3 Orthophoto Processing

Orthophoto processing eliminates image distortion caused by terrain relief. It requires correction using generated digital terrain model data combined with aerotriangulation results to produce orthophotos. As shown in Figure 2, the orthorectification process involves importing raw digital images and using DEM and triangulation results to create orthophotos. Once orthophotos are generated, each pixel in the image possesses geometric fidelity.

Every point in the image is projected orthogonally (perpendicularly) to the

Earth' s surface. By finding the equivalent point for each pixel in the aerial photograph through DEM, elevation displacement can be corrected. Subsequently, by referencing brightness values of surrounding pixels, each pixel' s brightness value can be redrawn and output. Using brightness values, elevation, and exterior orientation parameters, the equivalent position in the orthophoto can be calculated.

Compared with traditional correction techniques, orthorectification relies more heavily on digital elevation data. The digital elevation model created from stereo image pairs contains uncertainties due to limitations in the generation process, which consequently affects orthophoto quality. Therefore, digital elevation models have different accuracy levels depending on their intended purpose, with each level having uncertainty factors and associated error limits.

2.4 Aerial Triangulation

Aerial triangulation utilizes the parallax geometry principle in overlapping areas between adjacent aerial photographs and establishes spatial stereo geometric relationships based on the aerial positions of photography stations. Similar to ground triangulation methods, this measurement technique calculates point coordinates on photographs and spatial orientation of each photograph (Figure 3).

To determine the six exterior orientation parameters at the photography center, aerial triangulation employs the principle of resection. When the perspective center, image point, and corresponding three-dimensional object space point lie on a straight line, they become collinear, which can be described by the collinearity equation. As shown in Figure 4, points P, p, and O lie on the same straight line, with the collinearity equation being:

[Equation would appear here based on Figure 4 reference]

The collinearity condition equation can form six equations, which are ultimately solved to obtain the six exterior orientation parameters at the photography center. After obtaining the interior and exterior orientation parameters, the spatial coordinates X, Y, Z of conjugate points within overlapping photograph areas can be determined through space forward intersection. Figure 5 illustrates the concept of spatial forward intersection. Through the establishment of collinearity conditions, the perspective centers of two photographs intersect at a point in space via image points. By inputting the image coordinates of point p_1 from the first photograph and point p_2 from the second photograph, the spatial coordinates X , Y , Z of ground point P can be calculated through transformation using the collinearity equation and exterior orientation parameters.

2.5 Numerical Aerial Photogrammetry

This study utilized ERDAS IMAGINE software to establish a database for surface deformation analysis of landslide areas. The research employed singlecapture DMC digital camera imagery, which is a frame-format digital camera featuring eight lenses. The central four lenses produce high-resolution panchromatic imagery of 13,824 × 7,680 pixels, while the outer four wide-angle lenses capture four-band imagery in blue, green, red, and infrared.

This study applied numerical UAV photogrammetry with the objective of reconstructing digital terrain models (DTM) of landslides to facilitate subsequent analysis. Using numerical aerial photogrammetry combined with ERDAS IMAGINE' s LPS module, DTM generation and image correction processing were conducted through the following eight steps:

[Processing steps would be detailed here]

3 Results and Discussion

This study used raw aerial photographs captured by UAV and employed the Mosaic Pro function in the ERDAS IMAGINE Data Preparation module to mosaic individual digital terrain models and orthophotos into comprehensive DTMs and orthophotos covering entire watershed areas. Appropriate parameters were selected in Mosaic Pro to ensure final image integrity. Orthophoto results for various landslide regions are shown in Figures 6-7.

Ground control point (GCP) selection for this study utilized geodetic coordinates from referenced orthophotos. The criteria for selecting GCPs included:

1. Preferably choose points on the ground surface, such as sharp feature points at road intersections, playground corners, lakes, or field ridges.
2. Avoid selecting surface features with elevation, such as building corners or tree tops, as parallax caused by their height affects control point accuracy.
3. Each image requires at least three control points. Since this study used multiple aerial photographs, selected GCPs were distributed evenly across all aerial images.

Where x , y are the photograph coordinates of the image point; x_0, y_0 are the photograph coordinates of the principal point; X , Y , Z are the spatial coordinates of ground point P; X_1, Y_1, Z_1 are the spatial coordinates of the photograph' s projection center O; and m_{11}-m_{33} are elements of the rotation matrix formed by photograph rotation angles ω, ϕ, .

This study successfully applied numerical aerial photogrammetry technology to establish fine digital terrain models and orthophotos of landslide areas in Meizhou. By optimizing UAV aerial photography parameters (60% forward overlap, 20%-30% side overlap) and the ERDAS IMAGINE data processing workflow, the accuracy and efficiency of surface deformation analysis were significantly improved. Compared with traditional monitoring methods, this approach substantially reduces labor and time costs while overcoming data acquisition challenges in complex terrain. The research results not only provide high-precision spatial data for landslide disaster mechanism analysis but also establish a technical foundation for intelligent disaster early warning and prevention strategy development. Future work could further integrate multi-source remote sensing data with real-time monitoring systems to enhance dynamic landslide prediction capabilities.

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