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Research on Green and Low-Carbon Assessment Techniques for the Stability of High Slopes in Red Strata

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Abstract

This paper develops a rapid dynamic assessment framework for the stability of high red-bed slopes, integrating non-contact monitoring technology, numerical simulation analysis, and green low-carbon solutions. Specifically, high-precision point cloud data of the slope surface is captured using 3D laser scanning, while numerical simulations are performed with FLAC3D software to evaluate slope stability. Additionally, eco-friendly support materials such as recycled concrete and fly ash are incorporated to optimize carbon emission control. The research further introduces a rapid assessment platform for slope stability, providing robust support for dynamic monitoring and efficient evaluation of slope conditions.

Keywords

Red-layer high slopes, 3D laser scanning, Numerical simulation, Green and low-carbon practices, Stability evaluation.

1. Introduction

The stability of slope engineering is a critical concern in construction projects, particularly under complex geological conditions such as high red-bed slopes. Traditional methods for evaluating slope stability largely depend on field tests and empirical formulas, which are not only inefficient but also environmentally damaging. In recent years, with the growing emphasis on green and low-carbon principles, finding ways to ensure slope stability while minimizing the environmental impact of construction has become a key focus in the engineering field. This paper introduces a rapid dynamic assessment method for the stability of high red-bed slopes based on green and low-carbon concepts, incorporating non-contact monitoring technology, numerical simulation techniques, and sustainable low-carbon solutions.

2. Environmental Friendliness of Non-Contact Monitoring Technology

2.1. 3D Laser Monitoring Technology for Slope Deformation

Thanks to advancements in instrument manufacturing technology, 3D laser scanning technology has made remarkable progress. Its efficient and convenient operational model, along with intelligent data processing methods, has drawn significant attention across various fields. In the area of slope monitoring, the 3D laser scanner has emerged as a highly efficient and environmentally friendly monitoring solution, owing to its technical features such as non-contact measurement, high-precision and high-density point cloud data acquisition, 3D data visualization, and all-weather operability. These advantages enable 3D laser scanning technology to provide precise and sustainable technical support for slope monitoring.

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Acquire point cloud data of the slope surface using the Z+F IMAGER 5010 3D laser scanner, see Fig. 1.

Process the collected point cloud data using computer vision and image processing algorithms, including point cloud registration, reconstruction, and fitting, to generate more accurate terrain models and detailed slope structure information[1].

Fig. 1 Z+F IMAGER 5010 3D Laser Scanner

When collecting point cloud data of slopes, it is necessary to conduct on-site surveys, identify the scanning area, and select appropriate locations based on site conditions. Meanwhile, ensure there are at least three control points in different zones, and then unify all laser scanning data conversion values within a single coordinate system.

Point Cloud Data Processing Point cloud data processing can be divided into three parts: denoising, registration, and simplification[2].

Denoising is performed using statistical filtering and pass-through filtering to eliminate noise points. The process of denoising point cloud data involves handling noisy points while preserving valid point cloud data[3];

Registration processing transforms point cloud data into a unified coordinate system using plane targets. The essence of point cloud registration lies in geometric transformation operations such as rotation, translation, and scaling, which consolidate point cloud data from different coordinate systems into a single coordinate system. If it is necessary to convert relative coordinates into absolute coordinates, the following formula can be used to complete the conversion.

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} * R(\theta_1,\theta_2,\theta_3) * F + \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} \tag{1}$$

In the formula, X_1, Y_1, Z_1-Absolute coordinates of the point cloud;

X_0, Y_0, Z_0-The coordinate system inherent to the scanner itself;

F-The magnification factor, where F=1 when the scales of the two coordinate systems are the same;

δ_x , δ_y , δ_z -The distance of coordinate translation;

θ_1 , θ_2 , θ_3 -The angle between the axes of the absolute coordinate system and the corresponding axes in the laser scanner's coordinate system;

$R(\theta_1,\theta_2,\theta_3) = R_x(\theta_1) * R_y(\theta_2) * R_z(\theta_3)$ -This is the coordinate transformation matrix.

To achieve high-precision registration, at least three pairs of feature points are needed to calculate the six parameters in feature-point-based registration. The quality and extraction accuracy of these feature points directly influence the precision of coordinate transformation. Using highly reflective planar targets is an efficient and convenient way to obtain feature points.

(3)The simplified processing combines an octree structure with the ISS feature point extraction method, reducing the volume of point cloud data while preserving key features. First, the octree structure is employed to rapidly partition and downsample large-scale point cloud data, decreasing the data size and enhancing processing efficiency[4]. Then, following the octree-based division, the ISS feature extraction method is utilized to extract representative feature points from characteristic regions, further retaining the structural and feature details of the original point cloud and providing robust support for subsequent point cloud analysis and modeling tasks[5], see Fig. 2.

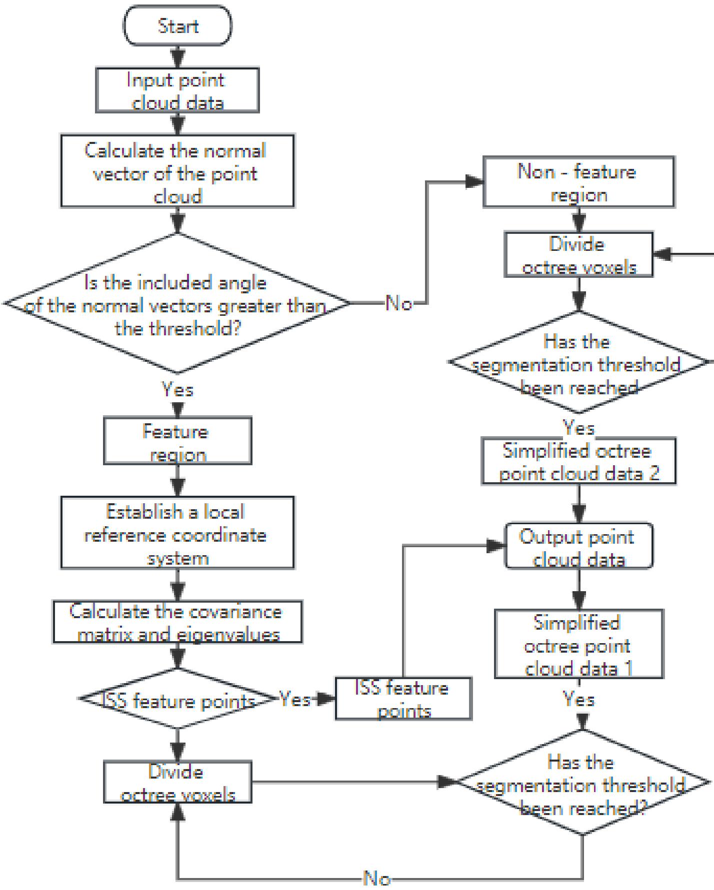

Fig. 2 Flowchart of the point cloud simplification algorithm incorporating a feature preservation mechanism

(4) Deformation Analysis

Table 1 Slope Monitoring Deformation Values

	Region 1	Region 2	Region 3	Region 4	Monitoring Area
Maximum Distance	440.41	89.27	136.67	−145.13	194.32
Average Distance	79.49	66.71	85.31	−82.02	0.43
Standard Deviation of Distance	23.39	11.61	25.59	−25.53	6.85

2.2. Numerical simulation reduces resource consumption

Numerical simulation technology based on FLAC3D uses computer modeling to replace some field tests, reducing material waste (such as concrete and steel) and the energy consumption of construction machinery in traditional engineering, in line with low-carbon principles. By optimizing slope support design through virtual simulation technology, over-support is avoided, cutting down on material usage and carbon emissions.

FLAC3D Numerical Simulation: This paper utilizes FLAC3D software to construct a numerical model of the slope and applies the Mohr-Coulomb constitutive model to describe the mechanical response of the slope's rock and soil mass. A systematic stability analysis is performed using the strength reduction method, enabling the precise determination of the slope's critical displacement threshold and providing a quantitative basis for subsequent risk assessment.

Model Construction: Based on the actual geological conditions of the slope, different rock and soil layers are defined, with corresponding material parameters assigned. The boundary conditions are specified as follows: the upper part of the model features a free boundary, the bottom is constrained by fixed boundaries, and horizontal displacement is restricted along the left and right boundaries, see Fig. 3.

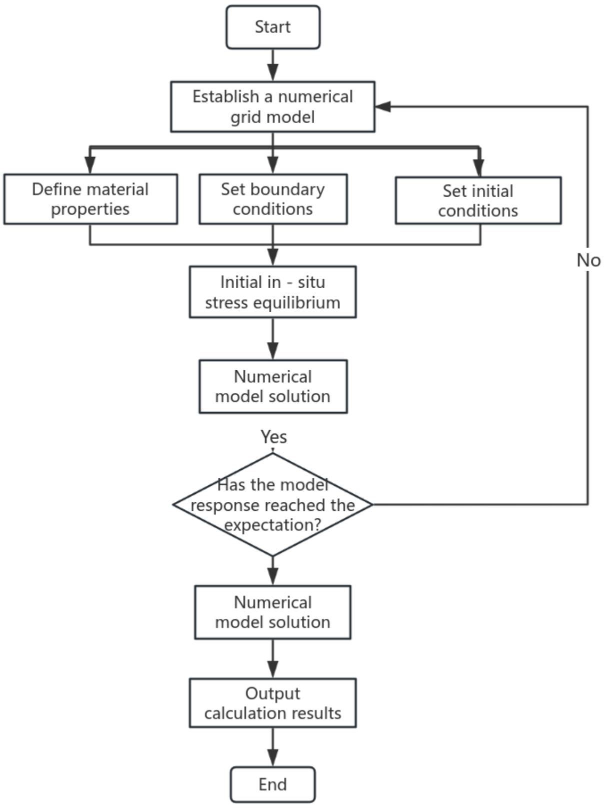

Fig. 3 FLAC 3D Numerical Model Analysis Workflow

3. Application of Green and Low-Carbon Technologies in Slope Engineering

3.1. Green Support Materials

Using anchor frame beam support can further integrate green materials such as recycled concrete and bamboo fiber-reinforced composites, reducing reliance on cement and steel while lowering embodied carbon. Ecological slope protection materials made from industrial waste (e.g., slag and fly ash) combine structural support with vegetation growth functionality. In exploring innovative applications of ecological slope materials, J.B. Niyomukiza et al.[6]successfully developed a novel type of ecological slope protection material by blending slag and fly ash, which effectively mitigates erosion and landslide risks. By incorporating specific ratios of slag and fly ash, the research team leveraged their chemical and physical properties to create a porous structure during the curing process, enhancing water retention and permeability[7], thereby fostering optimal conditions for root development and expansion. This material is simpler and more cost-effective to produce, while significantly cutting carbon emissions during its lifecycle, aligning with green and low-carbon development principles.

3.2. Rapid Assessment Platform for Slope Stability

To achieve the goal of rapid dynamic assessment of red-bed high slope stability, this paper develops an integrated platform for evaluating slope stability. The platform seamlessly integrates numerical slope models with surface deformation monitoring data, enabling real-time and highly efficient dynamic assessments of slope stability. Its creation and application not only significantly enhance the efficiency of assessment tasks but also innovatively achieve low-carbon management through advanced digital technologies, specifically demonstrated by:

Platform Development The development of the rapid slope stability assessment platform includes four core modules: engineering profile analysis, numerical simulation research, surface deformation monitoring, and the formulation of rapid assessment methods. During the numerical simulation phase, the FLAC3D software is utilized to construct a detailed numerical model. Through simulation calculations, the critical unstable and stable states of the slope are determined, and displacement data corresponding to these states are extracted as key thresholds for stability evaluation. For surface deformation monitoring, 3D laser scanning technology is employed to gather slope surface deformation data. Combined with point cloud processing techniques such as denoising, registration, and simplification, the slope deformation is precisely calculated. The processed data is then transmitted in real time to the assessment platform, providing robust support for subsequent stability evaluations. Processing and analyzing point cloud data yields geometric information about the slope, facilitating deeper insights into its structural and morphological characteristics. This enhances the comprehensiveness of data available for slope stability assessments.

Dynamic Assessment Process A 3D laser scanner is installed on-site at the slope, and using an automated data transmission system, monitoring data from the slope can be quickly transferred to the cloud for storage and further processing.```After performing preprocessing operations such as denoising, registration, and simplification on cloud-based point cloud data, deformation comparison analysis of the point cloud data can be conducted to determine the average deformation value of the monitoring area. The obtained deformation values are then entered into the surface deformation monitoring section. By comparing the cumulative surface deformation values with the displacement threshold, the stability of the slope can be quickly evaluated. Compared to traditional measurement methods, such as topographic surveying instruments or total stations, laser scanning technology eliminates the need for contact with the target object and can operate under various terrain conditions, reducing human interference and safety risks during the measurement process. Laser scanners are capable of rapidly collecting extensive terrain data, significantly saving measurement time and enhancing efficiency[8].

This process enables efficient and precise assessment of slope stability, offering robust support for the safety management of slope engineering, see Fig. 4.

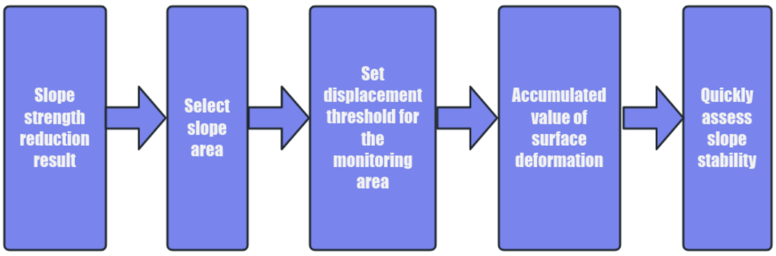

Fig. 4 Flowchart of Rapid Assessment Implementation Process for Slope Stability

4. Conclusion

This paper proposes a rapid dynamic assessment method for the stability of high red-layer slopes based on green and low-carbon principles by incorporating non-contact monitoring, numerical simulation, and green low-carbon technologies. Experimental results demonstrate that this method not only facilitates rapid dynamic evaluation of slope stability but also significantly reduces the environmental impact of construction projects, thereby advancing the sustainable development of slope engineering. Future research directions include further enhancing the performance of ecological support materials and refining the low-carbon management capabilities of the rapid slope stability assessment platform, offering more comprehensive technical support for the green and low-carbon advancement of slope engineering.

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