A Landslide Displacement Calculation Method Based on Correlation Analysis of Point Cloud Intensity Images

XIE Mowen¹, LIU Weinan¹, WANG Hongfei² and LI Qingbo²

1 School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
2 Yellow River Engineering Consulting Co., Ltd., Zhengzhou, Henan 450003, China
E-mail: s20160033@ustb.cn

Abstract. This article proposes a new point cloud data analysis method to expand the applicability of 3D laser scanning technology for landslide deformation monitoring. First, the laser intensity value of the point cloud needs to be corrected. The corrected, discrete point cloud data is converted into a two-dimensional false color image based on its laser intensity. Then, a digital image correlation algorithm is introduced to analyse the point cloud intensity raster images. The displacement field of the landslide on a specific projection plane is calculated. Finally, the calculated landslide displacement field is matched with the digital elevation model of the landslide. The spatial displacement field of the landslide surface was calculated by comparing the elevations before and after the deformation. Laboratory experiments show that this method can monitor the deformation and failure of the landslide model as well as calculate the spatial displacement of the landslide surface.

1. Introduction
Terrestrial laser scanning a planar monitoring technology, can be applied to acquire point cloud data on the target surface with high precision quickly. The three-dimensional data model of the monitored object is generated by point cloud data, and the local and overall deformation of the target can be measured accordingly.

The development of TLS technology greatly facilitates engineering surveying and deformation monitoring. XIE [1], CHEN [2], and WANG [3] have obtained good results of measurements on the tunnel deformation, foundation pit deformation, and earth-rock dam deformation with TLS technology. The spatial information in the point cloud data is used by all methods mentioned above. In practice, the point cloud data obtained by the TLS technology can record the spatial coordinate information of the laser point and contain the intensity information of the laser point [4]. ZHOU [5] have used the intensity information of the laser point cloud to extract features, which improves the efficiency of feature classification. Minh [6] and Scaioni [7] have coupled the intensity information of point cloud data with other information, which enhances the efficiency of target extraction for point cloud data. Coren [4] and CHEN [8] have converted point cloud data into reflection value images and found the deformation of the target by comparing the two-phase images of reflection value.

A slope deformation monitoring method with laser point cloud intensity information is proposed in this paper. The new method can eliminate the defects of existing point cloud data processing methods in slope deformation monitoring and enhance the potential of point cloud intensity information in TLS technology. It first utilizes the point cloud intensity correction formula to correct the original point cloud and then converts the spatial point cloud data into a two-dimensional false color image with the corrected laser intensity information. It adopts the Digital Image Correlation algorithm to process the two-phase
false color image to calculate its plane displacement field, and then register the plane displacement field with the slope 3D model to realize a fast calculation of the slope 3D displacement field. A slope model experiment is carried out. The measured displacement value at the reference point on the model surface is compared with the calculated displacement value to prove the usefulness of the method.

2. Analysis of point cloud intensity information

2.1. Point cloud intensity value
When the laser point emission and the reception time are recorded, the scanner can obtain the signal intensity value of the target’s reflected laser point as well. The value of the laser intensity reflected on the object surface is related to the intensity of the incident laser signal and the reflection characteristics. Different materials have varied absorption and scattering capabilities for laser light. Therefore, the intensity of the target reflection information received by the scanner is also various. The parameters related to the surface characteristics of ground features can be extracted from the intensity value of the point cloud [9, 10] due to the different reflectivity of the materials to the laser signal. Therefore, when the landslide deformation is monitored by the laser scanner, the change of the landslide surface features can be determined by the shift in the point cloud intensity value.

2.2. Point cloud intensity correction
During the emission to the reflection of the laser beam, the intensity of the laser’s echo for the point cloud is also affected by the environment, the incidence angle, the emission power of the device, and the inherent spectral reflection characteristics of the monitored target. The intensity value $I$ of point cloud data can be expressed by the following formula [11]:

$$I = f(\rho, R, \theta, P_e) = C \frac{P_e \rho \cos \theta}{R^2} \eta$$

(1)

where $C$ is the point cloud intensity correction factor, $\rho$ is the target reflectivity, $R$ is the scanning distance, $\theta$ is the laser incidence angle, $P_e$ is the scanner emission power, and $\eta$ is the laser one-way atmospheric transmission coefficient. If the scattering and absorption capabilities of the atmosphere between the scanner and the target are the same at the same time, the calculation formula of the laser one-way atmospheric transmission coefficient $\eta$ is as follows:

$$\eta = 10^{-2Ra/10000}$$

(2)

where $a$ is the atmospheric attenuation coefficient. When the atmospheric environment is relatively simple, or the monitoring range is rather small, the laser atmospheric transmission coefficient correction may fail to perform. However, if the monitoring range is large, or the meteorological data is rather complex, this correction is a necessity. The reference value is selected to unify the intensity of the multi-phase point cloud and collect result of the same laser scanner under a specific distance. The particular incidence angle and atmospheric conditions are chosen as well. The corrected point cloud intensity value can be expressed by the following formula:

$$I_c = I \frac{\cos \theta_s}{\cos \theta} \frac{R^2_s}{R^2} 10^{-2(R_s - Ra)/(10000)}$$

(3)

where $\theta_s$ is the reference incident angle, $R_s$ is the reference distance, and $a_s$ represents the reference atmospheric attenuation coefficient.

3. Calculation method of slope spatial displacement
The calculation process for the landslide spatial displacement using the intensity characteristics of the point cloud mainly includes three steps: point cloud data conversion (point cloud pseudo-reflection image generation), raster image analysis, and spatial displacement calculation.

3.1. Point cloud false-color image generation
It is still impractical to directly obtain the deformation value of the monitored target from the corrected point cloud intensity value. To quickly extract the displacement of the slope surface from the intensity information of multi-phase point clouds during landslide monitoring, the work of HU[12] is adopted, and the spatial interpolation algorithm is applied to interpolate discrete point cloud data into a false color image according to their intensity values.

Spatial interpolation algorithms include the Kriging method, the inverse distance weighting method, the spline function method, and the natural neighborhood method [13]. The point cloud data collected by TLS technology is continuous but unevenly distributed on account of the occlusion of surface features. The existence of these holes will bring a significant error to the point cloud interpolation. Considering the non-uniformity of point cloud data, an inverse distance weighted interpolation method is chosen to process the point cloud data [14]. The weight of the inverse distance weight interpolation is the reciprocal of the distance between the calculation reference point and the interpolation point in the targeted area. The calculation formula of the estimated value $Z_0$ at the point $(x_0, y_0)$ is as follows [15]:

$$Z_0 = \frac{\sum_{i=0}^{n} z_i f(d_{ij})}{\sum_{i=0}^{n} f(d_{ij})}$$

(4)

where $n$ represents the number of points in the targeted area, $z_i$ is the actual value of the calculated reference point, and $f(d_{ij})$ represents the weight coefficient between the calculated reference point and the interpolation point in the targeted area. The coefficient $f$ is inversely proportional to the distance between two points and can be generally expressed as follows:

$$f(d_{ij}) = \frac{1}{d_{ij}^b}$$

(5)

where $d_{ij}$ is the distance between the calculation reference point and the interpolation point, and $b$ is the calculation parameter.

### 3.2. Raster image analysis

With spatial interpolation technology, 3D point cloud data can be converted into 2D raster images. However, how to extract the deformation information of the target surface from the two images still calls for an effective method for processing. Therefore, digital image correlation technology, a non-contact surface deformation monitoring technology, is introduced to analyze the point cloud false color image. It adopts the gray-scale similarity matching method to analyze the digital images before and after the deformation of the monitored target. By calculating the change of the plane coordinates of the pixels in the sub-region, the vector displacement of the region can be solved. The principle is shown in Figure 1.

![Figure 1. Diagram of DIC technology principle](image)

Before starting the calculation, the image $F$ before the deformation and the image $G$ after the deformation are sampled first as images with the same pixel size. The calculation window $W$ and the search window $S$ are selected in line with the feature size. In the calculation, the image $F$ is adopted as the reference, and the calculation window in the image $G$ moves sequentially within the search window. By comparing the similarity of the pixels in the calculation window of the two images, the corresponding
positions of the feature in image F and image G are settled[16-18]. If \( I_F(x,y) \) is the pixel value of the calculation window in image F, and \( I_G(x,y) \) is that in image G, and when the calculation window moves in image G:

\[
I_g = I_g(x + i, y + j)
\]  
\[
(6)
\]

where \( i \) and \( j \) represent the displacements of the calculation window in the horizontal and vertical directions. Then the correlation coefficient of the pixel values of the window in the two images is as follows:

\[
R_{FG} = \frac{\sum_w (I_F - \bar{I}_F)(I_G - \bar{I}_G)}{\sqrt{\sum_w (I_F - \bar{I}_F)^2} \sqrt{\sum_w (I_G - \bar{I}_G)^2}}
\]  
\[
(7)
\]

where \( \bar{I}_F \) and \( \bar{I}_G \) are the average values of the pixels contained in the calculation window of image F and image G. As the calculation window displacements \( i \) and \( j \) changes, \( R_{FG} \) alters as well. Finally, a correlation coefficient matrix can be obtained, as shown in Figure 1c. When the \( R_{FG} \) reaches its maximum value, \( i \) and \( j \) are the displacement of the ground object in the calculation window of the image F. The plane displacement field of the monitored target in the entire image range can be achieved by adjusting the calculation window continuously.

3.3. Calculation of spatial displacement

When the DIC technology is applied to analyze the point cloud false color image, the calculation result can be considered as the plane displacement of the target on a certain projection surface. Combining the calculated horizontal displacement field of the landslide with the digital elevation model of the landslide, the starting point, and the ending point of the horizontal displacement can be determined by the coordinate point matching. The vertical size of the displacement vector is resolved with the DEM difference between the landslide body before and after the deformation. Its principle is shown in Figure 2. The plane coordinates are set before the landslide deformation and the monitoring subset to \( A'_F(x_F, y_F) \), the image correlation method is adopted to process the false color image of the point cloud. The plane coordinates \( A'_G(x_G, y_G) \) is calculated after the deformation of the monitoring subset. The x and y coordinate values are substituted into the digital terrain model before and after the deformation. Thus, the elevation value can be calculated. The spatial coordinates \( A_F(x_F, y_F, z_F) \) of the monitoring subset before the deformation can be obtained, and the spatial coordinates \( A_G(x_G, y_G, z_G) \) after deformation can also be gained. In this way, the spatial displacement of the landslide body surface can be determined.
4. Case study
Determining the spatial displacement of the landslide body is of considerable significance to the treatment of landslide disasters. In order to verify the effectiveness of the method mentioned above for landslide monitoring, model experiments were carried out.

4.1. Experimental model
The model was 100 cm in length, 60 cm in width, and 80 cm in height with a slope angle of about 60°, and 20 reflective points were laid on the slope (Figure 3). During the experiment, the slope was deformed with loading on the top of the slope. After each loading posed, the RIEGL VZ-400 three-dimensional laser scanner was applied to collect the point cloud data. The vertical and horizontal resolutions of the three-dimensional laser scanner were 0.005°.

4.2. Point cloud data processing
Equation (3) shows the point cloud intensity correction formula. In this experiment, the point cloud data of the landslide model contains the laser propagation distance $R$. As a result, only the incidence angle of the laser needs to be calculated. The laser incident angle $\theta$ is related to the digital terrain model of the monitored target and the laser emission angle, and its calculation formula is as follows:

$$\cos \theta = \hat{n}_i \cdot \hat{n}_e = (\sin T \cos P, \sin T \sin P, \cos P) \cdot (\sin A \cos S, \sin A \sin S, \cos S)$$

where $\hat{n}_i$ is the laser emission direction of the 3D laser scanner ($T$ and $P$ are the vertical and horizontal angles of the laser beam), and $\hat{n}_e$ is the normal direction of the landslide model surface ($A$ and $S$ are the aspect and slope of the landslide model). With ArcGIS to process the point cloud data of the landslide model, the distribution curve of its incident angle and the scanning distance can be obtained. To more realistically reflect the feature information of the slope model with the false color image, the reference distance is selected as the average of all point clouds, 5.58 m, and the reference incident angle is also selected as the average of all point clouds, 49.57°. In this paper, the point cloud data of the landslide model is calculated by interpolation at a distance of 2 cm.

4.3. Calculation result of spatial displacement of landslide
The slope model gradually loses its stability and fails as the load increases. The two sets of point cloud data before and after landslide deformation are exhibited in Figure 4. It can be seen from the figure that the sliding of the slope model results in evident cracks and collapses at the trailing edge, while the leading edge of the slope appears to be uplifted.

![Figure 3. Experimental Model of Slope](image1)

![Figure 4. Comparison of Two Scanned Point Cloud Data](image2)

To obtain the displacement field on the surface of the landslide model, the point cloud data is projected onto the horizontal plane. After spatial correction, the IDW interpolation method was applied to generate
false color images of the slope models before and after deformation. The DIC program is also used to process the two raster images. The size of the calculation window and query window in the program is set to 32mm and 64 mm, respectively. Through the correlation analysis of the two images, the plane displacement field of the landslide model can be calculated accordingly. The DEM interpolation results of the slope model and the plane displacement calculation results are recorded, as shown in Figure 5.

![Figure 5. Calculation results of landslide plane displacement and vertical deformation](image)

The plane displacement field and DEM of the landslide are recorded, and then the elevation value is calculated with the plane coordinates of the target point. Thus, the spatial position of the monitoring points on the slope surface can be obtained before and after the load, and the spatial displacement can be calculated when the slope slides, as shown in Figure 6.

To verify the usefulness of the spatial displacement of the landslide surface obtained with point cloud data, the results of the manual measurement of the spatial displacement are compared with the calculation results of the point cloud data in the reflective point on the slope surface. During the experiment, some of the reflective points are separated from the landslide model due to the cracks on the slope. Therefore, 15 reflective points on the slope surface are chosen to be the reference. The calculated value of the spatial displacement of the reference point is revealed by the interpolation. The calculated value of displacement and the measured value is shown in Figure 7. MVD, MHD, CVD, and CHD in Figure 7 represent the measured vertical displacement, the measured horizontal displacement, the calculated vertical displacement, the calculated horizontal displacement, respectively. It can be seen from the figure that the spatial displacement of the landslide calculated with point cloud data is consistent with the actual measurement results. The average absolute percentage errors of the calculated and measured displacements in the vertical and horizontal directions are 4.21% and 6.22%, separately, and their accuracy meets the requirements.

The experimental results demonstrate that the spatial displacement of the landslide surface can be calculated with the point cloud intensity characteristics and the spatial information, which provides favorable conditions for the monitoring of dangerous landslides, in which contact monitoring equipment cannot be deployed.
Figure 6. Calculation result of spatial displacement of landslide model

Figure 7. Comparison of calculation results of landslide spatial displacement

5. Conclusion
A new method is proposed to calculate the spatial displacement of the slope with the point cloud intensity characteristics in this paper. This method can obtain the spatial displacement field of the slope surface quickly by converting the discrete three-dimensional point cloud data into a two-dimensional plane image. The deformation of the slope surface can be calculated by analyzing the two-dimensional image. The method here avoids the direct comparison of point clouds in conventional displacement calculation and compares the false color images of point clouds instead. It prevents the complicated matching algorithm in the direct point cloud comparison and improves the processing speed of point cloud data. The main work of this method can be completed automatically with the calculation program, which effectively solves the additional errors caused by manually selecting the “deformation monitoring block” in the “gravity method” or the “fitting method” [19]. It can also expand the application of TLS technology in the landslide deformation monitoring.

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