Research on Fast Calculation Method of Complex Soil Yard Excavation Volume Based on 3D Laser Scanning

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Abstract. The measurement of earthwork excavation in hydropower project construction is an important control process in engineering construction. The traditional measurement and calculation process is not only inefficient, but also easy to cause errors. In this paper, the 3D laser scanner is applied to continuously measure the excavation process of the soil material yard and the efficient processing method of registration, compression and extraction process of excavation point cloud data is established respectively. At the same time, two fast calculation methods of excavation volume based on point cloud data are established. The practical application proves the data processing method established in this paper can shorten the data processing time by more than 80%, and ensure the accuracy of the data, and can control the calculation error of the excavation volume within 1%.

1. Introduction

The core-wall rock-fill dam has been widely used in the construction of hydropower projects in southwestern China in recent years [1]. The core wall is the core anti-seepage structure of the dam. The quality of the anti-seepage material is strictly controlled. For the ultra-high core dam, the demand for anti-seepage material is huge, and it is usually required to supply from multiple materials yards. In the material yard mining process, it is necessary to accurately record the mining volume to control the mining progress. Due to the large difference in spatial position, transportation distance and reserves of each material yard, the topographical features are different, which cause the mining methods are different. The current engineering measurement is mainly based on the measurement of the area of several excavation sections, which is multiplied by the section spacing. This method has different results due to the difference in section selection, and it takes time and effort.

In recent years, 3D laser scanning technology has been optimized for slope excavation in hydropower projects due to its high efficiency, high precision. It is widely applied in slope excavation quality control [2, 3], river improvement [4], landslide analysis [5] and the calculation of excavation volume [6-9]. However, the above research is mostly carried out by scanner’s post-processing software, and the processing efficiency is low. In this paper, the 3D laser scanning technology is used to continuously measure the excavation process of the soil field, and the rapid registration and compression method of the excavation point cloud data is established, which realizes the efficient processing of the point cloud data of the excavation surface. At the same time, two methods for
calculating the excavation volume of the material yard based on point cloud data are established, which realizes the accurate measurement of the mining material quantity. The engineering application shows that the method established in this paper can improve the efficiency and accuracy of the calculation of the excavation volume of the material yard, and provide a scientific basis for the management and control of the material yard mining.

2. Excavation surface scanning and data processing

The scanner used in this paper is the Leica Scan-Station C10. The maximum theoretical scanning radius is about 300m, and the highest scanning accuracy is 100m/1cm. In the field practice, the scanning precision is 100m/2cm, and the scanning time per station is about 3min.

2.1. Point cloud registration

The data of the soil material field usually needs multi-station multi-view scanning to obtain complete data, and the coordinate system of the point cloud data of each station is isolated from each other. Subsequent processing needs to convert it to the same coordinate system. This conversion process is called point cloud registration. Currently, the mainly registration algorithms are: ICP \(^{[10]}\) algorithm, and Bursa-Wolf \(^{[11]}\)Model, virtual feature point \(^{[12]}\). In this paper, a simple registration algorithm based on the Bursa-Wolf model is established. The three-dimensional spatial relationship is shown in Figure 1. The same as the upward, the conversion needs to first rotate around the z axis, and then the translation of x, y, z can be performed, so the conversion model can be expressed as follows:

\[
\begin{bmatrix}
    X \\
    Y \\
    Z
\end{bmatrix}
= 
\begin{bmatrix}
    \Delta X \\
    \Delta Y \\
    \Delta Z
\end{bmatrix}
+ 
\begin{bmatrix}
    \cos \theta & \sin \theta & 0 \\
    -\sin \theta & \cos \theta & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    X' \\
    Y' \\
    Z'
\end{bmatrix}
\]

(1)

In formula (1), \(\Delta X\), \(\Delta Y\), \(\Delta Z\) are panning parameters, \(R(\theta)\) are the rotation matrix around the z axis, it is expressed as follows:

\[
R(\theta) = 
\begin{bmatrix}
    \cos \theta & \sin \theta & 0 \\
    -\sin \theta & \cos \theta & 0 \\
    0 & 0 & 1
\end{bmatrix}
\]

(2)

As shown in figure 2. XOY is the target coordinate system, \(xoy\) is the geodetic coordinate system. The point o is origin of coordinate. The control points are common points both in two coordinate systems, and the values of the common points in the geodetic coordinate system can be measured by RTK and Scanner. The origin coordinates o, the geodetic coordinates of control point 1 and control point 2 are respectively recorded as \((X_o, Y_o, Z_o)\), \((X_1, Y_1, Z_1)\), \((X_2, Y_2, Z_2)\) the relative coordinates of the origin, control point 1 and control point 2 are \((0,0,0)\), \((x_1, y_1, z_1)\), \((x_2, y_2, z_2)\).

Then the following equation can be obtained from the geometric relationship:
\[
\Delta y = \frac{\Delta y \tan \theta}{\Delta y - \frac{\Delta y}{\cos \theta}} \\
\Delta x = \frac{\Delta X - \Delta X \tan \theta}{\Delta x - \Delta y \tan \theta} \\
Z = Z_0 + z_i
\]

(3)

In which: \( \Delta x = x_i, \Delta y = y_i \).

Solving separately \( \Delta X, \Delta Y, \Delta Z \), then control point 1 world coordinates \( X, Y \). They are:

\[
\begin{align*}
X &= X_0 + \Delta X \\
Y &= Y_0 + \Delta Y \\
Z &= Z_0 + \Delta Z
\end{align*}
\]

(4)

By analogy, all scanned data can be converted to world coordinates.

The actual world coordinates and registration coordinate data pairs of the 5-station data in one measurement are shown in Table 1, which proves the accuracy of this method.

| Site | Measuring actual world coordinates | Post-registration coordinates | Difference |
|------|------------------------------------|--------------------------------|------------|
|      | \( X \) | \( Y \) | \( Z \) | \( X \) | \( Y \) | \( Z \) | \( X \) | \( Y \) | \( Z \) |
| 1    | 3738662.6806 | 267508.3750 | 2923.2758 | 3738662.6705 | 267508.3941 | 2923.3091 | -0.0101 | -0.0191 | -0.0332 |
| 2    | 3738722.6044 | 267592.2807 | 2920.2922 | 3738722.6199 | 267592.2652 | 2920.3312 | -0.0155 | 0.0155 | -0.0390 |
| 3    | 3738733.2344 | 267685.8453 | 2915.6802 | 3738733.2370 | 267685.8277 | 2915.6927 | -0.0026 | 0.0176 | -0.0125 |
| 4    | 3738730.7262 | 267807.4737 | 2910.4848 | 3738730.7049 | 267807.4465 | 2910.5263 | 0.0213 | 0.0272 | -0.0415 |
| 5    | 3738705.3930 | 267950.2586 | 2917.6798 | 3738705.4036 | 267950.2181 | 2917.7083 | -0.0106 | 0.0406 | -0.0285 |

2.2 Point cloud compression

The soil material field has the characteristics of large area and uneven surface of the excavation surface. After registration, a large amount of redundant data will be generated, and redundant data will reduce data processing efficiency. Therefore, it is necessary to compress the data. The current compression methods mainly are improved octree \[12\], curvature grading \[13\], and adaptive slice-based point cloud compression algorithm. These algorithms have ideal effects in retaining the feature information of point cloud data, but the adaptability of various algorithms is not very strong, and the efficiency is not high enough, and the parameters are often difficult to control.

By analysing the feature of the scanning data, this paper proposes a point cloud data compression method based on hyper-geometric space sphere. Compared with the previous series of methods, the algorithm is more compact in form and more efficient to execute. When the parameters are set, the feature information of the point cloud can be better preserved. The calculation model is as follows:

In a set of point cloud \( \text{Cloud} = \{p_1, p_2, ..., p_n\} \). Set \( p_i \) as base point, establish a hyper-geometric spatial sphere as \( p_i \) center point, \( R \) as radius, this space called field. Then at the given \( R \) value, if the point cloud \( \text{Cloud}_{\text{subset}} = \{p_1, p_2, ..., p_n\} \) fall in \( R \) field, then delete \( \text{Cloud}_{\text{subset}} \) and keep base point \( p_i \). At this point, a compression is completed. When select the nearest point to \( p_i \), called \( p_i \), then repeat above process until all the point cloud data are compressed. The flow chart is shown in Figure 3.

The above method is used to compress a set of data. The point cloud images before and after compression are shown in Figure 4(a) and (b) respectively. From the test data (see Table 2), the proposed method has high compression efficiency and can retain the characteristics of origin cloud.
Delete point set \( \{p_k, ..., p_j\} \)

Establish a space sphere with \( p_i \) as its center and \( R \) as its radius

Save spherical center \( p_i \)

Retrieve point sets located in \( \text{sphere}(p_k, ..., p_j) \)

Delete point set \( \{p_k, ..., p_j\} \)

Save spherical center \( p_i \)

Update point cluster \( P_i \)

Is \( p_i \) the last point of the new point cloud?

Finish

Figure 3. Point cloud compression flowchart

(a) before compression (1003)       (b) after compression (433)

Figure 4. Comparison before and after compression

| Original point cloud | Delete point cloud | Remaining point cloud | Compression ratio | time cost(s) |
|----------------------|--------------------|-----------------------|-------------------|--------------|
| 1003                 | 570                | 433                   | 56.83%            | 0.2532       |

2.3 Excavation area data extraction

In order to ensure the integrity of the data, the scanning range needs to be larger than the boundary of the excavation area. In order to facilitate the precise management of the excavation area, the data outside the excavation area needs to be deleted after the data is registered and compressed. In this paper, an excavation boundary data extraction method based on intersection point discrimination is established. The principle is that each excavation area forms a polygon from its boundary point coordinates. For any point \( p \) in a set of point cloud data, pass point \( p \) to \( x \) axis. The direction leads to a ray. If the number of intersections of the ray and the polygon is odd, the point \( p \) is in the excavation area, and the point \( p \) is reserved. If the number of intersections is even, the point \( p \) is deleted, and thus the cycle completes all the processing of the point is shown in Figure 5.
3. Soil material mining measurement method

The amount of soil material mining is a key indicator of project schedule and cost control. The traditional metering process is mainly obtained by measuring the area of several typical sections and multiplying the thickness between the sections. This method requires measurement of multiple section data. For the section with complicated shape of excavation, it is necessary to increase the number of measurement sections. According to the point cloud data obtained before and after excavation in the excavation area, two volume calculation methods are proposed, which are stratified accumulation method and prism accumulation method.

3.1 Stratified accumulation method

The point cloud data of the two scans before excavation and after excavation are started from the bottom surface, and the contour data is extracted according to certain layer spacing, and the two sets of data are combined with the elevation data, so that each elevation data can form a polygon. The polygon, as shown in Figure 6, calculates the area of each layer polygon, and then multiplies the layer spacing, that is, the volume of the layer is obtained, and the volume of all the layers is accumulated to obtain the total volume, that is, the excavation volume. The layer spacing can be dynamically adjusted to the accuracy requirements.
As shown in the above figure, the blue point cloud data indicates the original contour data of an excavation site, and the orange point cloud data indicates the contour data after the excavation of the portion, and the area enclosed by the two sets of data is the excavated area. Knowing the coordinate information of each point, the area of the polygon can be calculated by the following formula.

\[
Area(P_i) = \frac{1}{2} \sum_{i=0}^{n-1} (x_iy_{i+1} - x_{i+1}y_i)
\]

(5)

Then calculate the total volume by the following formula:

\[
V = \int_{a}^{b} Adh = \sum_{k=0}^{m} Area(P_k) \Delta h
\]

(6)

Where: \(V\) represents the total volume, \(\Delta h\) indicates the layer thickness, \(Area(P_k)\) indicates the volume of the \(k\)th layer, and \(P_i\) represents the point cloud data of the \(k\)th layer.

3.2 Prism accumulation method

The point cloud data before excavation and excavation are extracted separately. According to the excavation boundary size and accuracy requirements, the excavation area is divided into several regular quadrilateral grids from the plane. Figure 7 shows that the actual volume of the excavation body is obtained by arranging the eight vertices on the front and rear curved surfaces to form a quadrangular prism and calculating its volume, and accumulating the volume of all the quadrangular prisms in the excavation area.

The volume calculation formula is as follows:

\[
V = \sum_{i=1}^{n} x_i y_i / h_i
\]

(7)

Among them: \(x_i\) indicates the width of the bottom surface of the \(i\)th cylinder, \(y_i\) indicates the length of the bottom surface of the \(i\)th cylinder, \(h_i\) indicates the height of the \(i\)th cylinder.

![Figure 7. Schematic diagram of cylinder cutting](image)

3.3 Comparative analysis

For the excavation data of a certain group, the above two methods are used for comparative analysis. The horizontal spacing and the grid spacing are all calculated by 1m. The results are shown in Table 3. It can be seen from the results that the calculation efficiencies of the two methods are basically equivalent. However, the relative error of the prism accumulation method is much smaller than the stratified accumulation method.
Table 3. Earthwork calculation results

|                        | Volume (m$^3$) | Spacing | Relative error(%) | Time (s) |
|------------------------|----------------|---------|-------------------|----------|
| Measured volume        | 24462.500      | /       | /                 | /        |
| Hierarchical accumulation | 25770.510     | 1m      | 5.347             | 7.810    |
| Prismatic accumulation method | 24541.905   | 1m      | 0.224             | 8.260    |

4. Engineering applications

A core wall rockfill dam is located in the south-western China, with a core wall filling quantity of about 4.4 million m$^3$, and five soil material yards are planned. The P soil material field is divided into three areas A, B and C according to the terrain (Figure 8). The excavation order is A area→C area→B area. In order to scientifically control the excavation process, the excavation process is used to track and scan the excavation process by using 3D laser scanning technology. The image of the image after the final completion of excavation in Area A is shown in Figure 9.

Figure 8. P yard terrain map

Figure 9. The map of A area of P yard after excavation

Through the method established in this paper, the scanning time of the entire excavation surface is about 2h, the data post-processing time is about 1h, and the original point cloud data is about 190,000, and the point cloud data after excavation is about 1.45 million, passing through the stockyard before and after excavation. The three-dimensional solid model was measured and the excavation volume was 779,522 m$^3$. The mining and volume and time-consuming data calculated on the I7 7700HQ and 16G memory computers were calculated by the calculation method established in this paper and the different computational grids were selected.

Table 4. Excavation volume calculation results

| NO. | Number of Grids | Time consuming(s) | Excavation volume(m$^3$) | Error(%) |
|-----|-----------------|-------------------|--------------------------|----------|
| 1   | 100             | 6.33              | 785603                   | 0.78     |
| 3   | 300             | 45.34             | 786270                   | 0.87     |
| 4   | 500             | 275.28            | 786403                   | 0.88     |

It can be seen from Table 4 that the more the number of grids, the exponential growth of calculation time, but the error does not change much. It can be seen that the method established in this
paper can greatly improve the efficiency and accuracy of the calculation of the excavation volume of the soil material yard.

5. Conclusion
In this study, a 3D laser scanner was used to study the calculation method of the mining amount of complex soil material field. The main conclusions are as follows:

1) A simple point cloud registration model is established. Only the relative origin and the coordinates of the two control points and the geodetic coordinates can be used to achieve data registration, which improves the accuracy and efficiency of measurement coordinate conversion.

2) A point cloud data compression method based on hyper-geometric space sphere is established, which realizes the fast compression processing of scanned redundant data. A method based on the ray method for extracting point cloud data inside the boundary is established, which can quickly delete the cloud data of the invalid point outside the mining area.

3) Based on the point cloud data, the layered accumulation method and the prism accumulation method are respectively used to calculate the excavation quantity. The application results show that both methods can quickly calculate the excavation volume, and the prism accumulation method has better adaptability and calculation accuracy.

4) Engineering practice shows that the method proposed in this paper can provide a scientific basis for the management and control of soil material mining.

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