Data processing in analysing landslide in the mountainous area by geodetic methods

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Abstract: The task of processing displacement monitoring data and conducting deformation analysis presents a significant challenge. It necessitates not only precise data processing but also the application of an appropriate adjustment method that is in compliance with a specific process related to construction. Although adjustment methods share a common correction number for the measured values, the resulting adjusted coordinates or height differ. This paper employs landslide simulation data from the Mong Sen Bridge in Sa Pa, Lao Cai, and various adjustment methods to process the data. The outcomes of the displacement calculations are then compared to validate the aforementioned issue. However, an accurate comparison and analysis of displacement can only be achieved when the same adjustment method is consistently applied across all cycles. The results of the analysis are also precise and reliable. Furthermore, it is crucial to consider the size of the monitoring region when selecting an adjustment method to ensure that the simulation results and the trend of the landslide closely resemble reality.

1. Introduction

The system for monitoring networks, such as those used for landslide monitoring, can be structured as either a one-level or two-level network, comprising the base network and the monitoring network. The style of work and monitoring plan dictate whether data processing (adjustment) is conducted using a relative or absolute network [1]. Adjustment methods, including dependent network adjustment, free network adjustment with some stable points, and free network adjustment based on all points, are implemented through the principle of least squares [2,3].

The results obtained from these adjustment methods differ if the adjusted coordinates of points are selected as parameters, due to the varying systems of benchmarks. Utilizing the adjusted coordinates in a network without a consistent system of benchmarks for structural displacement analysis often yields incorrect results, leading to inaccurate conclusions about the state of the work [4,5,6]. Furthermore, displacement analysis also relies on the trend of structural displacement to provide a reliable evaluation. This paper conducts an experiment to analyze the displacement results in the landslide area at Mong Sen Bridge, Sapa, Lao Cai, demonstrating that different adjustment methods yield varying results. This underscores the necessity of unifying the adjustment method across all cycles and selecting the relative or absolute method based on the scale of the construction to ensure that the results align with the displacement trend.

2. Theoretical base and the monitoring method

2.1. The process of geodetic network adjustment

When a network of displacement monitoring is adjusted with the indirect adjustment method, the process of calculation includes the following steps [7]:

Choose the adjusted coordinates of points without coordinates to be the unknown, symbol the unknown vector as δX, proximate coordinate vector as X_0

Establish the system of correction equations as follows :

$$A\delta X + L = V \tag{1}$$

Where: A is the coefficient matrix, δX is the unknown vector, V, L are the correction vector and free number vector. If the network is free, there is lack of positioning elements, so the equation system (1) has dependent columns (the number of dependent columns equal the missing number d)

Based on the least square principle to transit the correction equation system to the standard system:

$$R\delta X + b = 0 \tag{2}$$

With $R = A^T PA; \quad b = A^T PL$

Matrix R depending on the adjustment method is calculated as follows:

If the network is dependent or has enough original data, R is non-degenerate matrix, *Det (R) # 0,* solutions of equation (2) :

$$\boldsymbol{\delta X = -R^{-1}b} \tag{3}$$

If the network is free, R is degenerate matrix, *Det (R) = 0* so it is unable to solve the system by normal method because equations has infinitely many solutions

To determine the unique solution vector, add a binding condition system of the unknown vector, as form:

$$C^T \delta X = 0 \tag{4}$$

The system (4) has to satisfy two conditions:

The number of conditions equal the missing number

Rows in the matrix $\boldsymbol{C^T}$ are linear independence to rows in matrix A

Combine (2) and (4), based on the indirect adjustment method with conditions, a expand standard system is established

$$\begin{bmatrix} R & C \\ C^T & 0 \end{bmatrix} \times \begin{bmatrix} \delta X \\ K \end{bmatrix} + \begin{bmatrix} b \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{5}$$

The coefficient matrix in (5) can be inverted normally and has form of block matrix.

$$\begin{bmatrix} R & C \\ C^T & 0 \end{bmatrix}^{-1} = \begin{bmatrix} R^{\sim} & T \\ T^T & 0 \end{bmatrix} \tag{6}$$

Solution of system (5) is determined by the formula:

$$\delta X = -R^{\sim} b \tag{7}$$

There are many ways of calculating the pseudo-inverse matrix, for example as:

$$R^{\sim} = (R + CP_0C^T)^{-1} - TP_0^{-1}T^T \tag{8}$$

$$\boldsymbol{T = B(C^T B)^{-1} T} \tag{9}$$

Where B is Helmet coordinate transition matrix

In the plane network with $d = 4$, matrix B is calculated as follows:

$$B_i = \begin{bmatrix} 1 & 0 & y_i & x_i \\ 0 & 1 & -x_i & y_i \end{bmatrix} \tag{10}$$

$$B = \begin{bmatrix} B_1 & B_2 & .... & B_k \end{bmatrix}^T$$

Notes: formula (9) is right for the plane network (x, y, □, m) - free, if an original element is definite, the corresponding column no exists in the mentioned formulas

Accuracy evaluation is implemented through normal formulas of the indirect adjustment method with conditions

Mean square error of unit weight is calculated as:

$$\mu = \sqrt{\frac{V^T PV}{n-k+d}} \tag{11}$$

Where: n is sum of the measured values, k is the essential value

2.2. Establishment of the landslide displacement monitoring network

The deformation monitoring network is able to be established as two formats: the relative network and the absolute network. The absolute network comprises points situated outside the deformation area, which serve as benchmarks. The relative network includes all points lying in the deformation area. In instances where the deformation region and its impact are minimal, the monitoring network is typically constructed as an absolute network, as exemplified in hydroelectric dams, construction sites, and small landslide areas, as depicted in Figure 1. However, when the deformation area is exceptionally large or undefined, a relative network is established, resulting in a network devoid of benchmarks. This is often the case in scenarios involving crustal deformation, geological fissure monitoring, and the effects of earthquakes and volcanoes, as illustrated in Figure 2 [1].

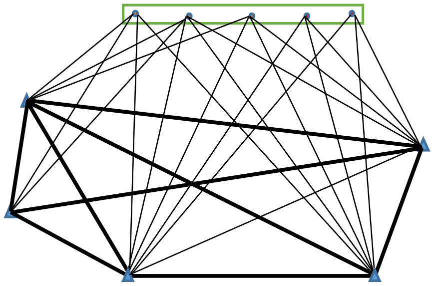

Figure 1. The hydroelectric dam monitoring network

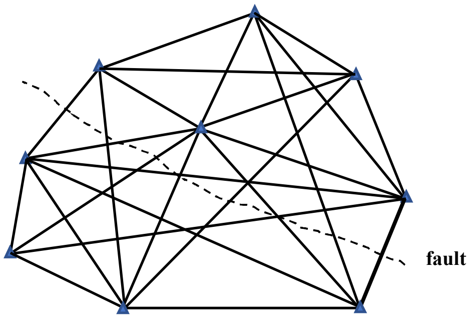

Figure 2. The fault monitoring network

In the context of an absolute network, points are situated outside the landslide area and are referred to as benchmarks or reference points.. These points facilitate the determination of the absolute displacement of points within this area. Consequently, these benchmarks are strategically positioned on stable geological locations, distanced from the landslide area, or embedded within the original rock layer. This arrangement ensures that the displacement values obtained from the monitoring points within the landslide area represent absolute displacement.. However, benchmarks may also experience displacement due to various factors, such as being placed on unstable strata or being affected by external conditions. In monitoring process, to detect the unstable benchmarks, a large number of benchmarks should be layout to form the framework. This framework is measured in cycles to evaluate the stability of the benchmarks, followed by the correction of any unstable benchmarks. In contrast, with a relative network, all points are located within the landslide area, and only the application of the entirely free adjustment method can yield reliable results [4].

3. Experiment model

3.1. Modelling area

Area at Mong Sen bridge, Sapa, Lao Cai has weak geological condition, always happen landslide in the rainy season. This place has strongly divided terrain with steep banks and dangerous 3-level bends on national highway 4D connecting Lao Cai to Sapa. Lao Cai province has just allowed to clear the bridge that is across the valley and has the highest pillar in the north in August, 2023 to avoid the 3-level bends, reduce risks and shorten the moving time of vehicles. Image of the landslide area at Mong Sen bridge from Google Earth, the base points (triangular) and monitoring points (square) are shown in figure 3.

Figure 3. The landslide region at Mong Sen bridge (Source: Google Earth)

3.2. Calculation and analysis of the landslide data

3.2.1. Accuracy estimation. With Mong Sen monitoring area as figure 3, the article designs the absolute network including 5 benchmarks (MC1-MC5) that are far from landslide region, 9 monitoring points are located in the landslide region (QT1-QT9), figure 4. Firstly, accuracy estimation for the monitoring network needs implementing to choose equipment and instrument in order to ensure the requirement accuracy. The allowance error of position is 15 millimetres [8]. Therefore, according to [7] mean square error of position of the base network and the monitoring network is calculated, respectively as follows:

$$m_I = \frac{m_p}{\sqrt{1+k^2}} = \frac{15}{\sqrt{1+4}} = \frac{15}{\sqrt{5}} = 6.7m \tag{12}$$

$$m_{II} = \frac{2\times m_p}{\sqrt{1+k^2}} = \frac{2\times 15}{\sqrt{1+4}} = \frac{30}{\sqrt{5}} = 13.2mm \tag{13}$$

Using two adjustment methods for four models to compare and choose the suitable one with real displacement. The adjustment methods are given in table 1, where the adjustment method for the fourth model is the one for the relative network, in which equipment is no put at monitoring points to measure.

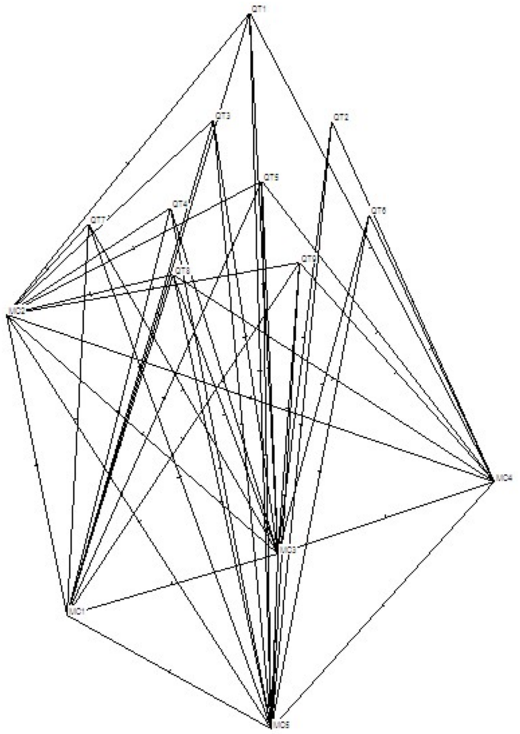

Figure 4. The designed monitoring network

Table 1. Expected adjustment models

Nº	The adjustment methods	Notes
1	Adjustment for the dependent network	the side measuring network
2	Free adjustment with origin as central point of three stable benchmarks	the side measuring network
3	Free adjustment with origin as central point of five stable benchmarks	the side measuring network
4	Free adjustment with origin as central point of all points	the side measuring network

Implement accuracy estimation for four mentioned cases, equipment is an electronic total station with error of side measurement $m_s=3+2ppm$. The designed network is the side measuring ones so that measurement is swift, no affected by environment. In case 1, all base points are entirely stable, measure 38 sides. The other cases measure 56 sides as figure 4. Results of estimation are represented in table 2.

Table 2. Results of accuracy estimation

Nº	points	Coordinate X(m)	Coordinate Y(m)	error of position m_p(mm)			
				Case 1	Case 2	Case 3	Case 4
1	QT1	9321.0	6770.0	5.0	5.1	5.1	4.6
2	QT2	9230.0	6838.0	9.0	9.6	9.6	8.6
3	QT3	9231.0	6740.0	5.3	5.6	5.6	5.3

4	QT4	9157.0	6704.0	4.3	4.5	4.4	4.3
5	QT5	9179.0	6780.0	3.7	3.8	3.7	3.7
6	QT6	9151.0	6870.0	7.1	7.6	7.6	7.1
7	QT7	9143.0	6635.0	4.3	4.5	4.5	4.4
8	QT8	9101.0	6706.0	3.3	3.4	3.3	3.3
9	QT9	9111.0	6811.0	3.4	3.5	3.4	3.4
10	MC1	8815.0	6617.0	0.0	2.4	1.7	2.0
11	MC3	8866.0	6793.0	0.0	2.3	1.7	1.8
12	MC2	9067.0	6567.0	0.0	1.2	1.4	2.1
13	MC4	8927.0	6974.0	0.0	1.5	1.7	2.1
14	MC5	8719.0	6788.0	0.0	1.5	1.6	1.8

The table 2 shows that the weakest point in all cases is QT2, the weakest error of position is 9.6 millimetres in the second and the third model. All cases satisfy error of position of the monitoring network in formula (12). This proves that electronic total station with medium accuracy can be used to monitored.

3.2.2. Results of model calculation. The designed network, comprising 56 measured values of side, was assessed using the electronic total station TC703, which has a side measurement error of $m_s = 3+2ppm$. Subsequent data processing was conducted for the four models under consideration. If the coordinates listed in columns 3 and 4 of Table 2 are regarded as the adjusted coordinates from the previous cycle, the coordinate correction number equates to the displacement of points. Table 3 presents the displacement of points in the coordinate axis, while Table 4 provides information on the smallest positional error. Figure 5 illustrates the error ellipse of points across all models.

Table 3. Adjustment results

N°	Point	Displacement in coordinate axis (mm)							
		Case 1		Case 2		Case 3		Case 4	
		δX	δY	δX	δY	δX	δY	δX	δY
1	QT1	1.5	3.8	1.6	3.8	1.6	3.8	1.5	3.5
2	QT2	1.8	4.1	2.0	7.7	2.0	7.7	1.9	6.9
3	QT3	1.8	3.3	2.0	4.3	1.9	4.3	1.8	4.1
4	QT4	1.6	2.7	1.9	3.4	1.8	3.4	1.7	3.4
5	QT5	1.7	3.4	1.7	2.7	1.7	2.7	1.6	2.7
6	QT6	1.8	2.3	1.9	6.2	1.9	6.2	1.8	5.8
7	QT7	1.7	2.3	1.8	3.6	1.8	3.6	1.6	3.5
8	QT8	1.9	7.2	1.9	2.3	1.8	2.3	1.7	2.3
9	QT9	1.9	5.8	1.8	2.4	1.7	2.4	1.6	2.4
10	MC1	0.0	0.0	1.2	1.7	0.8	1.2	1.0	1.3
11	MC3	0.0	0.0	0.7	0.8	0.9	0.8	1.2	1.3
12	MC2	0.0	0.0	1.2	1.5	0.9	1.1	0.9	1.2
13	MC4	0.0	0.0	0.8	1.0	1.0	1.1	1.3	1.2
14	MC5	0.0	0.0	0.9	0.9	0.8	1.2	0.8	1.3

Table 4. The position error of the weakest point

N°	Point	*The position error of the weakest point* mm)

		Case 1	Case 2	Case 3	Case 4
(1)	(2)	(3)	(4)	(5)	(6)
1	QT2	7.5	8.0	8.0	7.2

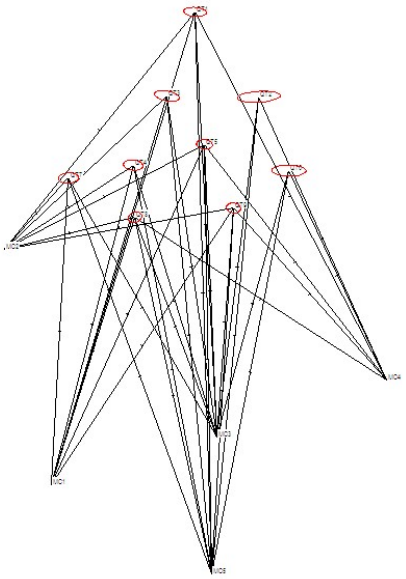

Figure 5a. Case 1 (5 fixed original points)

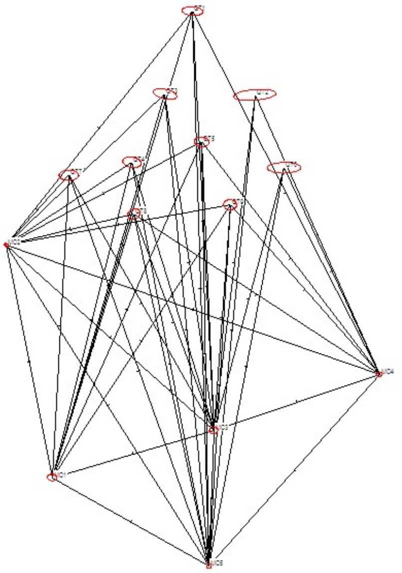

Figure 5b. Case 2 (origin is center of three stable benchmarks)

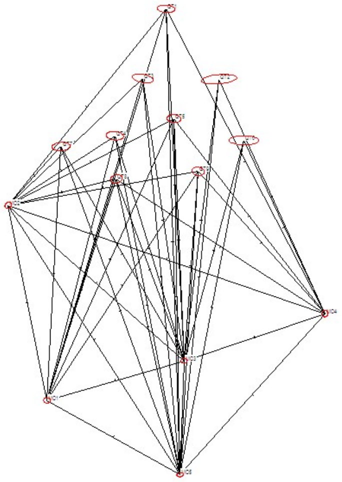

Figure 5c. Case 3 (origin is center of five stable benchmarks)

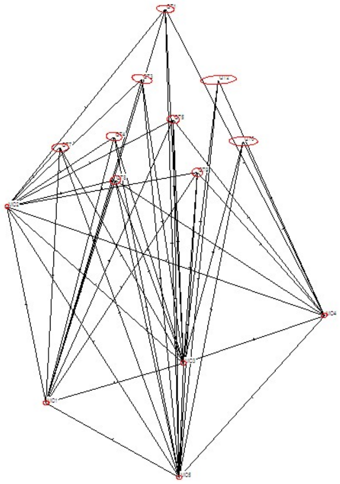

Figure 5d. Case 4 (origin is center of all points)

Figure 5. Error Ellipse of all points

4. Discussion and conclusions

4.1. Discussion

Upon analyzing a single cycle of data, it is observed that the four adjustment models yield equivalent positional errors, thereby ensuring a similar estimation problem. However, several distinctions are noted:

In the first model, ‘dependent network adjustment’, the network comprises two ranks, whereas the other models feature a one-rank network.

In the first model, benchmarks are assumed to be entirely stable, hence exhibiting no displacement. Consequently, data processing is primarily conducted for the base network, with benchmarks remaining stable and error-free. In the second and third models, if data processing is performed separately as per the calculation process, these revert to the first model. Post-adjustment, it is observed that the correction values increase with the distance of the monitoring points from the origin. However, the calculated displacement values closely resemble the actual values.

In the second, third, and fourth models, the correction values of the benchmarks represent the displacement of these points. If these displacement values exceed the permissible error, calculated using the stability standard k*mI (k=3, mI as per formula 3.11), the benchmark is deemed unstable and is subsequently removed from the system. If the unstable benchmark continues to be used for calculating the displacement of monitoring points, it necessitates correction, followed by readjustment.

In the fourth model, the positional errors of all points are relatively equal, given that the origin is the central point of all points. This validates that for large monitoring areas, this model yields the most uniform displacement result in the landslide region, as the center of this region is selected as the origin.

The displacement of monitoring points calculated using different methods varies, indicating that the number of benchmarks chosen for adjustment influences the displacement values. Therefore, to accurately calculate the displacement of monitoring points, the number of benchmarks needs to be consistent across cycles used for displacement comparison. This ensures that the analysis and assessment are reliable.

4.2. Conclusions

For smaller monitoring regions, the use of an absolute network, which includes two ranks, is recommended as it yields more accurate results. If a free network is employed, the stability of benchmarks must be analyzed. Stable benchmarks, which are devoid of error, necessitate the application of a calculation process for the absolute network.

For larger monitoring regions, the relative network is advised. The most suitable method in this scenario is the free adjustment method, with the central point of all points serving as the origin.

The selection of the adjustment method in the processing of monitoring data significantly influences the calculated displacement values. Therefore, to ensure reliable results, it is essential to maintain consistency in the adjustment method across all cycles.

5. References

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