The Application of Coordinate Similarity Transformation Model for Stability Analysis in High-precision GPS Deformation Monitoring Network

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KEY WORDS: GPS Deformation Monitoring, Stability Analysis, Coordinate Similarity Transformation Model, Hydropower Station

ABSTRACT:

This paper firstly analyzes the theory of coordinate similarity transformation, and a novel method of stability analysis for datum points applied in high-precision GPS deformation monitoring network is then put forward. The coordinate similarity transformation model is adopted to calculate transformation parameters for station coordinates of two adjacent periods. By comparing the transformed results and the network adjustment solutions, the station stability is verified. In order to judge the stability of stations, "the threshold of station stability" and "statistical test based on variance ratio" are developed. It is applied to stability analysis of three periods' datum points in an A-order GPS deformation monitoring network for hydropower station to verify the feasibility and effectiveness of this method.

1. INTRODUCTION

Stability analysis of GPS deformation monitoring network is one of the most important part of deformation observation data processing. For the periodical measurements of high-precision GPS deformation monitoring network, the best situation for deformation analysis is that a fixed datum is set up for all the time periods (Zhou Mingduan et al, 2011). The prerequisite of the above method is that adjustment datum remains stable among all the periods of observation. But the stability of datum points in high-precision GPS deformation monitoring network needs to be proved. We can not completely ensure that the adjustment datum point still remains stable because of the impact of surrounding environment. If the datum is not stable, and we still adopting the datum as fixed, the results of deformation analysis would be distorted (Gao Yaping, 2005). In order to seek for stability analysis methods of deformation monitoring network, many scholars and experts have done a lot of research work. For example, Mean spacing method, data snooping method, full permutation and combination method, bayes discrimination approach and robust iterative weights method and so on are typical methods (Tao Benzao, 2001; Hao Chuancai, 2003; Huang Shengxiang et al, 2010; Chen Chao et al , 2010; Huang Bingjie et al ,2011).

On the basis of analyzing the theory of coordinate similarity transformation and considering the characteristics that the transformation coordinates of common points are not the same as the known coordinates values because of the impact of errors of coordinates of common points, coordinate similarity transformation model is applied to stability analysis of high-precision GPS deformation monitoring network, and a novel stability analysis method of datum points for which the characteristics of similarity transformation have been only considered is put forward. This method has the advantages of simple calculation, without considering how to select adjustment datum point, and without unifying reference framework and epoch. Thus, it is better practicability and higher reference value.

2. STABILITY ANALYSIS MODEL BASED ON SIMILARITY TRANSFORMATION

2.1 Seven Parameters Similarity Transformation Method

Seven parameters similarity transformation method is one of the most essential and common models of three-dimensional Cartesian coordinate transformation. It is shown as Figure 1 (Guo Jiming et al, 2011).

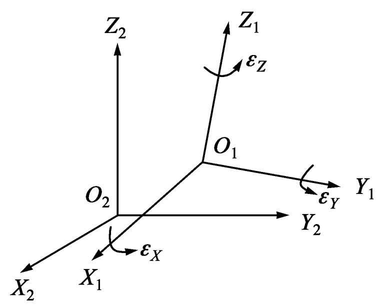

Figure 1． Seven parameters similarity transformation

For the periodical measurements of high-precision GPS deformation monitoring network, if we denote the coordinates of one datum point for two periods are $(X,Y,Z)_I$ and $(X,Y,Z)_{II}$ respectively, in the case of small rotation angles, the similarity transformation equation can be expressed as:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{II} = (1+k)\begin{bmatrix} 1 & \varepsilon_Z & -\varepsilon_Y \\ -\varepsilon_Z & 1 & \varepsilon_X \\ \varepsilon_Y & -\varepsilon_X & 1 \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_I + \begin{bmatrix} \Delta X_0 \\ \Delta Y_0 \\ \Delta Z_0 \end{bmatrix} \quad (1)$$

where $\Delta X_0, \Delta Y_0, \Delta Z_0$ are three translation parameters;

$\varepsilon_X, \varepsilon_Y, \varepsilon_Z$ are three rotation parameters;

k is a scale parameter.

Generally, the displacement of datum points is not very large in high-precision GPS deformation monitoring network, therefore, Eq. (1) is a linear model. When the number of common points is not less than three points, the optimal probability values of seven parameters can be obtained by least squares adjustment. And then, the process of coordinate similarity transformation can be realized and stability analysis model based on seven parameters similarity transformation can be constructed by using obtained seven transformation parameters.

2.2 Evaluation Method of Station Stability

In the process of similarity transformation, three-dimensional Cartesian coordinates of both pre-periodical and post-periodical have measurement errors or even may be the displacement of datum points, thus the calculated transformation parameters would be impacted if still using Eq.(1). Under the assumption condition that the impact of measurement errors of coordinates for transformation parameters is determined, the process of coordinate similarity transformation could be realized according to the calculated transformation parameters. For the impact of the point position displacement of three-dimensional Cartesian coordinates of both pre-periodical and post-periodical, the difference of between the transformed three-dimensional Cartesian coordinates and the known coordinate values would become larger which can be used as an evaluation criterion. And then stability analysis of point position in high-precision GPS deformation monitoring network can be carried out and comprehensive evaluated by using “the threshold of difference method” and “statistical test method based on variance ratio”. (Guo Jiming et al, 2011).

2.2.1 The Threshold for Station Stability

In high-precision GPS deformation monitoring network, if three-dimensional Cartesian coordinates of both pre-periodical and post-periodical only have measurement errors without the displacement of point position, the differences of point position between the transformed three-dimensional Cartesian coordinates and the known coordinate values would be under a limited value. In this way, the calculation formula of the differences of coordinate components (X, Y and Z respectively) between the transformed three-dimensional Cartesian coordinate and the known coordinate values can be expressed as:

$$V_{II} = X_{II} - X_{II}^{Trans} \tag{2}$$

Applying the covariance propagation law to Eq. (2):

$$\sigma_{V_{II}}^2 = \sigma_{X_{II}}^2 + \sigma_{X_{II}^{Trans}}^2 \tag{3}$$

Also, applying the covariance propagation law to Eq. (1):

$$\sigma_{X_{II}^{Trans}}^2 = (1+k)^2 \sigma_{X_I}^2 \tag{4}$$

Substituting Eq. (4) into Eq. (3), there is:

$$\sigma_{V_{II}}^2 = \sigma_{X_{II}}^2 + (1+k)^2 \sigma_{X_I}^2 \tag{5}$$

If $\sigma_{X_I} = \sigma_{X_{II}} = \sigma_X$, considering the scale parameter k is too little generally, so yielding to:

$$\sigma_{V_{II}}^2 \approx \sigma_{X_{II}}^2 + \sigma_{X_I}^2 = 2\sigma_X^2 \tag{6}$$

For the periodical and repetitious measurement of high-precision GPS deformation monitoring network, if assuming the nominal precision of GPS receivers used in the field observations of both pre-periodical and post-periodical is $\sigma_P = \sqrt{a^2 + (b \times D)^2}$, where a is solid error, b is ratio error, D is real average side length. For the specific datum point, there is $\sigma_P = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$; if letting $\sigma_X = \sigma_Y = \sigma_Z$, there is:

$$\sigma_X = \frac{\sigma_P}{\sqrt{3}} \tag{7}$$

Substituting Eq. (7) into Eq. (6), there is:

$$\sigma_{V_{II}} = \sqrt{\frac{2}{3}} \sigma_P \tag{8}$$

Assuming that there are *n* datum points in the high-precision GPS deformation monitoring network, since measurement errors of three-dimensional Cartesian coordinates in both pre-periodical and post-periodical observations, the impact of differences of coordinate components (X, Y and Z respectively) between the transformed three-dimensional Cartesian coordinates which are used by transformation parameters and the known coordinate values can be expressed as:

$$\sigma_{V_{II}} = \sqrt{\frac{2n}{3}} \sigma_P \tag{9}$$

If twice accuracy of field measurement (mean square error) is used as the allowable value of the limited error of differences between the transformed three-dimensional Cartesian coordinates and the known coordinate values, the allowable value of the limited error at the direction of space point position should satisfy Eq. (10), or the datum point is judged as change.

$$V_P \le 2 \cdot \sqrt{2n} \sigma_P \tag{10}$$

2.2.2 Statistical Test Based on Variance Ratio: In high-precision GPS deformation monitoring network, the similarity transformation method is carried out by using three-dimensional Cartesian coordinates of both pre-periodical and post-periodical observations. According to the difference values between the transformed coordinates and the known coordinate values, the estimation of unit weight root mean square error can be calculated by:

$$\sigma_0(n)=\sqrt{\frac{V^T PV}{f_n}} \tag{11}$$

where V is the difference value between the transformed coordinates and the known coordinate value.

f_n is the degree of freedom;

P is weight matrix of observation value (in this paper, the unit weight $P=E$).

After the coordinate similarity transformation, the point with the largest difference value of space point position is marked as M_1. Assuming M_1 point may be the displacement of point position and so deletes it. Then we do the process of similarity transformation again by using three-dimensional Cartesian coordinates of the remaining $n-1$ points in pre-periodical and post-periodical. Similarly, $\sigma_0^2(n-1)$ can be calculated. Then the point with the largest space point position is found and marked as M_2. Finally, we used F-test method and let the statistic as:

$$F_{n\text{-}1}^{n}=\frac{\sigma_0^2(n)}{\sigma_0^2(n-1)} \tag{12}$$

Thus, it determines the acceptance region of hypothesis test:

$$F_{n\text{-}1}^{n}<F_{\alpha}\left(f_n, f_n-m\right) \tag{13}$$

where $m=3$.

If the significant level α =0.05 is given, and Eq.(13) is established, M_1 point with the largest difference value of space point position is considered relatively stable and then all of the points in the network are considered relatively stable; conversely, if Eq.(13) is not established, M_1 point maybe is considered with the displacement of point position.

Repeating the above process of similarity transformation and applying statistical test method based on unit weight variance ratio to judged stability of remain points with the largest difference value of space point position until all of points are seek for which they maybe change.

3. EXAMPLE

In this paper, it selects three periodical and continuous GPS observation data which comes from an A-class GPS deformation monitoring network for a hydropower station to be tested and analyzed. There are seven datum points in the network which are observed by using forced centering piers. The GPS network figure is shown as Figure 2.

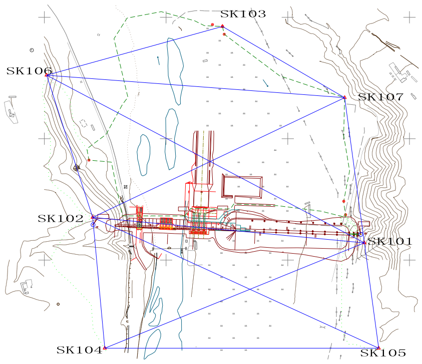

Figure 2. GPS deformation monitoring network for the hydropower station

The network was firstly constructed and observed from 2, Nov 2008 to 8, Nov 2008. According to the distribution of IGS stations and survey area situation of GPS stations, considering the precision of IGS station coordinates and data quality of IGS station, finally, URUM station and GAUO station (both of the global satellite tracking station) were selected as datum stations. The coordinates of the above two stations were obtained from IERS official website, and the precision of their geocentric coordinates was ±(3~8)mm. URUM station, GAUO station and SK101 datum point were used for constructing datum coordinate transmission network in order to obtain the adjustment initial coordinates for high-precision GPS deformation monitoring network. The first repetitious measurement of the network was observed from 11, Nov 2009 to 19, Nov 2009. The observation data of URUM station and GAUO station can not be obtained because of power failure. Finally, KIT3 station, LHAZ station, ULAB station (all of the global satellite tracking station) and SK101 datum point were used for constructing datum coordinate transmission network in order to obtain adjustment initial coordinate for high-precision GPS deformation monitoring network. The second repetitious measurement of the network was observed from 11, Sep 2011 to 16 Sep 2011. To keep consistent with the firstly conducted network, URUM station, GAUO station and SK101 datum point still were used for constructing datum coordinate transmission network in order to sequentially obtain the adjustment initial coordinate for high-precision GPS deformation monitoring network in repetitious observations. In the process of data processing, the same GPS data analysis software was used for calculating and analyzing three periodical GPS observation data respectively. The baseline solution strategies were completely identical in data processing. Baseline vector, variance matrix and other information with basis equal precision and without gross error were obtained, and then, it made free net adjustment processing and stability analysis of A-order datum points for GPS network respectively.

3.1 The Traditional Method by Fixing Datum Points

Under the premise of ensuring adjustment datum is that the unity of reference framework and epoch, we found that SK101 datum point located at a rocky which was considered as stable by means of experience, therefore, it could be used as the fixed datum point for stability analysis of point position. The literature (Zhou Mingduan et al, 2011) described stability analysis of A-class datum points between the firstly constructed observation and the firstly repetitious measurement, the results of analysis show: within the limits of measurement error allowable value, SK105 was judged as change and other datum points were stable relatively. After the field exploration, we found that there was a crack (width of about 8 cm, length of about 200 m) along the mountain body and the distance from the crack to SK105 point was about 100 m, as Figure 3 shows.

Figure 3. The crack of near SK105 point

Similarly, stability analysis of A-order datum point of twice repetitious measurements was made by using the method which referred the literature (Zhou Mingduan et al, 2011). According to the difference values between three-dimensional Cartesian coordinates of seven datum points after later data processing and of which previous corresponding coordinate results, and comparing and analyzing the difference values between independent engineering plane coordinate and geodetic height after fixing some datum point and one direction adjustment, and of which previous corresponding coordinate results, the difference values (the pre-periodical subtracts the post-periodical) were given in Table 1.

Datum point	Differences of three-dimensional Cartesian coordinate				Differences of plane coordinate			Differences of geodetic height	Judgment results
	X	Y	Z	displacement	N	E	plane	H	
SK101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Stable
SK102	-1.9	2.2	-1.8	3.4	-0.2	2.4	2.4	0.2	Stable relatively
SK103	-1.7	-0.1	-1.1	2.0	0.6	3.4	3.5	-1.1	Stable relatively
SK104	-0.9	-1.3	-4.6	4.9	-0.2	-0.1	0.2	-4.2	Stable relatively
SK105	**-4.0**	**248.3**	**188.5**	**311.8**	**-30.7**	**35.9**	**47.2**	**308.0**	**Change**
SK106	-1.8	-1.2	-3.4	4.0	1.2	2.9	3.1	-3.3	Stable relatively
SK107	-1.4	3.5	-1.7	4.1	-3.3	3.0	4.5	1.2	Stable relatively

Table 1. The difference values of point position coordinates between two repetitious measurements of GPS deformation monitoring network (unit: mm)

As is shown in Table 1, the difference values of point position coordinates between twice periodical observation results show that the X-direction, Y-direction and Z-direction of datum points including SK102, SK103, SK104, SK106 and SK107 in WGS-84 coordinate system are within 4.6mm, and the displacements are among 2.0~4.9mm, and the geodetic height are within 4.2mm. In independent engineering coordinate system by “fixed one point and one direction adjustment”, N-direction and E-direction are within 3.4mm, and the difference values of plane coordinate are among 2.4~4.5mm. If twice precision of field measurement (mean square error) is used as the allowable value of the limited error of difference between twice periodical observation results, the five datum points are judged as remaining stable relatively in the range of allowable value of measurement error. But for the difference of three-dimensional Cartesian coordinates of SK105 datum point, X-direction is 4.0mm, Y-direction is 248.3mm, Z-direction is 188.5mm, the displacement of point position is 311.8mm and H-direction is 308.0mm. In independent engineering coordinate system, the difference value of N-direction is 30.7mm, E-direction is 35.9mm and the displacement of point position is 47.2mm. If twice mean square error of point position is used as the allowable value of the limited error of difference between twice periodical observation results, datum point SK105 is judged as change in the range of allowable value of measurement error, and the reasons needed to be analyzed.

3.2 The Threshold of Stability

According to the above mentioned method, the corresponding program is developed using C++ language. Stability analysis model based on similarity transformation is constructed and the changing of point position between three-dimensional Cartesian coordinate after similarity transformation and known coordinate is used as the evaluation criterion. The results of numerical analysis are given in Table 2.

Point name	The first similarity transformation			The second similarity transformation		
	Differences of space point position	Threshold of difference	Judgment results	Differences of space point position	Threshold of differences	Judgment results
SK101	0.0261	0.0374	Stable relatively	0.0020	0.0346	Stable relatively
SK102	0.0038	0.0374	Stable relatively	0.0034	0.0346	Stable relatively
SK103	0.0079	0.0374	Stable relatively	0.0016	0.0346	Stable relatively
SK104	0.0256	0.0374	Stable relatively	0.0031	0.0346	Stable relatively
SK105	**0.0450**	**0.0374**	**Maybe change**	----	----	----
SK106	0.0143	0.0374	Stable relatively	0.0011	0.0346	Stable relatively
SK107	0.0122	0.0374	Stable relatively	0.0017	0.0346	Stable relatively

Table 2. Stability analysis of the first measurement and the first repetitious measurement of the GPS deformation monitoring network (unit: m)

As is shown in Table 2, in the process of the first similarity transformation, SK105 point might have been displaced and it is judged as maybe change. After SK105 point is deleted, the second similarity transformation is done again, the remaining six points are judged as stable relatively. Therefore, the above results show that all of the points are stable relatively except SK105 point.

Similarly, stability analysis of A-order datum points of twice repetitious measurements is done; the results of numerical analysis are given in Table 3.

Point name	The first similarity transformation			The second similarity transformation		
	Differences of space point position	Threshold of difference	Judgment results	Differences of space point position	Threshold of differences	Judgment results
SK101	0.1059	0.0374	**Maybe change**	0.0022	0.0346	Stable relatively
SK102	0.0186	0.0374	Stable relatively	0.0029	0.0346	Stable relatively
SK103	0.0325	0.0374	Stable relatively	0.0014	0.0346	Stable relatively
SK104	0.0862	0.0374	**Maybe change**	0.0016	0.0346	Stable relatively
SK105	**0.1611**	**0.0374**	**Maybe change**	----	----	----
SK106	0.0541	0.0374	**Maybe change**	0.0010	0.0346	Stable relatively
SK107	0.0362	0.0374	Stable relatively	0.0018	0.0346	Stable relatively

Table 3. Stability analysis of twice repetitious measurements of GPS deformation monitoring network (unit: m)

As is shown in Table 3, in the process of the first similarity transformation, SK101, SK104, SK105, SK106 points might have been displaced and it is judged as maybe change. However, the displacement of SK105 point is the largest, thus, if SK105 point is deleted, the second similarity transformation is done again, the remaining six points are judged as stable relatively. Therefore, the above results show that all of the points are stable relatively except SK105 point.

3.3 Statistical Test Based on Variance Ratio

According to the suggested method, the statistical test method based on unit weight variance ratio is used for determining stability of the datum points. Firstly, two three-dimensional Cartesian coordinates of seven datum points of the first constructed observation and the first repetitious measurement are used for doing coordinate similarity transformation, and then $\sigma_0^2(7)$ =2.69cm^2 can be obtained. If SK105 point is deleted because of the largest space difference value, the remaining six points whose three-dimensional space Cartesian coordinates are used for doing the second coordinate similarity transformation, also, $\sigma_0^2(6)$ =0.03cm^2 can be obtained. Thus, the statistic can be expressed as F_6^7 = 89.67. However, $F_{0.05}(14,11)$ =2.74, and obviously $F_6^7 > F_{0.05}(14,11)$. That is to say, SK105 point maybe has been displaced. If SK105 is deleted, the same approach is used for the remaining six datum points to do the similarity transformation again. SK102 point is got with the largest space difference value, therefore, if SK102 point is deleted, $\sigma_0^2(5)$ =0.02cm^2 can be obtained again. Thus, the statistic can be expressed as F_5^6 =1.50. However, $F_{0.05}(11,8)$ =3.31, and obviously $F_5^6 < F_{0.05}(11,8)$. That is to say, SK102 point is a stable point. Therefore, the above results show that all of the points are stable except SK105 point.

Similarly, the datum points of twice repetitious measurements are used for doing stability analysis by using the same method. Firstly, two three-dimensional Cartesian coordinates of seven datum points are used for doing coordinate similarity transformation, and then $\sigma_0^2(7)$ =35.88cm^2 can be obtained. If SK105 point is deleted because of the largest space difference value, the remaining six points whose three-dimensional space Cartesian coordinates are used for doing the second coordinate similarity transformation, also, $\sigma_0^2(6)$ =0.02cm^2 can be obtained. Thus, the statistic can be expressed as $F_6^7 = 1794.00$. However, $F_{0.05}(14,11)$ =2.74, and obviously $F_6^7 > F_{0.05}(14,11)$, That is to say, SK105 point maybe has been displaced. If SK105 is deleted, the same approach is used for the remaining six datum points to do the similarity transformation again. SK102 point is got with the largest space difference value, therefore, if SK102 point is deleted, $\sigma_0^2(5)$ =0.01cm^2 can be obtained again. Thus, the statistic can be expressed as F_5^6 =2.00. However, $F_{0.05}(11,8)$ =3.31,and obviously $F_5^6 < F_{0.05}(11,8)$, That is to say, SK102 point is a stable point. Therefore, the above results show that all of the points are stable except SK105 point.

According to the above discussion, it is an effectual method to synthetically evaluate the stability of datum points in high-precision GPS deformation monitoring network by using "the threshold of difference method" and "statistical test method based on variance ratio". Compared with the traditional method, this method has the advantages of simple calculation and without considering how to select adjustment datum, and the unity of reference framework and epoch.

4. CONCLUSIONS

On the basis of analyzing the theory of coordinate similarity transformation, a novel method of stability analysis for datum points applied in high-precision GPS deformation monitoring network is put forward. Compared with the traditional method, this method has the advantages of simple calculation, without considering how to select adjustment datum point, and without unifying reference framework and epoch. The method applied to stability analysis of an A-order GPS deformation monitoring network for a hydropower station with three periodical GPS observation data, the analysis results show that the suggested method in this paper can be applied to stability analysis of datum points in high-precision GPS deformation monitoring network, and the judgment results can be in agreement with the actual situation. Therefore, the feasibility and effectiveness of this method are verified. It provides a new solving thought and approach for stability analysis of datum points.

REFERENCES

Chen Chao, Zhang Xianzhou, 2010. Applications of bayes criterion in analysis on stability of deformation monitoring points based on false rate. *Railway Investigation and Surveying*, (6). pp.20-22.

Gao Yaping, 2005.The base stability analysis of GPS deformation monitoring and suppressing the surveying data noise by adaptive kalman filtering. *Chang'an Universtiy*, Xi'an.

Guo Jiming, Wang Jianguo, 2011. Foundation of Geodesy. *Surveying and Mapping Press*, Beijing.

Guo Jiming, Zhou Mingduan, 2011.Statistical testing in the gross error analysis of initial datum for GNSS network constraint adjustment, *The 1st International Workshop on Surveying and Geospatial Information Systems*, Fushun, China,pp.162-170.

Hao Chuancai, 2003. Studying several problems of the stability test of points in deformation monitoring network. *Southwest Jiaotong University*, Chengdu.

Huang Shengxiang, Yin Hui, Jiang Zheng, 2010.The data processing of deformation monitoring (the second edition). Wuhan University Press, Wuhan.

Huang Bingjie, Xiao Jianhua, Yan Xiaoping et al, 2011. Calculation of robust iterative weights and stability analysis in deformation monitoring networks. *Geotechnical Investigation & Surveying*, (3), pp.67-71.

Tao Benzao，2001.Free network adjustment and deformation analysis. *Wuhan Technical University of Surveying and Mapping Press*, Wuhan.

Zhou Mingduan, Guo Jiming, Xu Yinglin et al,2011.Data processing and stability analysis of GPS deformation monitoring network for hydropower station. *Bulletin of Surveying and Mapping*, (7), pp.30-33.

BIBLIOGRAPHY

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ACKNOWLEDGEMENTS

It acknowledges that the experiment data in this paper was provided by Institute of Surveying and Mapping, Investigation and Design for Water Resource and Hydropower Research Institute of Xinjiang. It acknowledges that GAMIT software was authorized by MIT. This work was supported by "the Fundamental Research Funds for the Central Universities" (No. 20102140101000002).