

Data processing and analysis of crustal deformation monitoring in the Fildes region, West Antarctica

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Received September 8, 1997

Abstract In order to research contemporary crustal movement of Antarctica, China has constructed the deformation monitoring network in the Fildes Strait region, West Antarctica, monitored the network by using DI-20 geodimeter and GPS instruments, and participated the Antarctic GPS Campaign Observation organized by SCAR as well. During mathematics processing of crustal horizontal deformation observations, a method to bring deformation parameters into the error equations of observations is discussed in this paper. Several classical deformation models, such as rigid body displacement and strain, are introduced. By analyzing the reference datum of static and dynamic geodetic network, the method is developed to set up different additional weight matrix for every different kind of parameter. A series of programs are developed to implementing the method mentioned above and the analysis of West Antarctic Fildes Strait deformation monitoring network. Discussion is also made of GPS monitoring data by using the principle of monitoring network strain analysis in the paper. The research results indicate that the displacement did occur in Fildes rift region, but the displacement was not large, just a slight rift shear movement.

Key words Antarctica, deformation monitoring, data processing, strain analysis.

1 Introduction

In the recent years the SCAR organized and led the GPS observing work that monitors crustal movement in Antarctica and gathered data many times by GPS receivers. In order to research contemporary crustal movement of Antarctica, China has constructed the deformation monitoring network in the Fildes Strait region, West Antarctica, monitored the network by using DI-20 geodimeter and GPS instruments, and participated the Antarctic GPS Campaign Observation organized by SCAR as well.

The South Shetland and the Antarctic Peninsula are located between South America Plate and Antarctic Plate. In this region there existed many small plates, such as Scotia Plate, South Sandwich Plate and South Orkney Plate. Besides, fault movement was very active in there because of interaction of the small plates. In modern times, the formation of Bransfield Strait expand center is the most significant crustal motion of the region (Li *et al.* 1992). It is very important to monitor modern crustal movement of the region by using high precise geodetic technique.

2 Data processing of Fildes deformation monitoring network

2.1 The crustal horizontal deformational model

The crustal horizontal deformation is very complex in factor of time and space. The main deformational feature of one region can be stated with some simple models on the assumption of crustal deformation in the region for a certain period. Suppose the studied body area is an even strain field in space and its deformation value is also even in time, so the area can be divided into more small rigid bodies. The deformation equation of one small rigid body is as follows:

$$du_{k_i} = \begin{bmatrix} du_{x_i} \\ du_{y_i} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -Y_i & X_i & 0 & Y_i \\ 0 & 1 & X_i & 0 & Y_i & X_i \end{bmatrix} \cdot [da_k db_k dw_k d\epsilon_{xk} d\epsilon_{yk} d\epsilon_{xyk}]^T \quad (1)$$

where: da_k, db_k are rigid body displacement value horizontally; dw_k is rigid body whirl value; $d\epsilon$ are interior even strain values; k is the number of the small body; x, y are coordinates of a point; du is displacement vector.

The displacement vector can be gotten from coordinate estimate value using phase adjustment. Because there are different reference datum for every phase observed data, a method to bring deformation parameters into the error equations of observations is discussed in this paper. The error equation of a phase observed data for range network adjustment can be formulated as follows:

$$V_q = B_\mu \cdot d\hat{\mu}_q + B_X \cdot d\hat{X}_q + B_\epsilon \cdot d\hat{\epsilon}_q - F_q \quad (2)$$

where, V_q : correct value of q th phase observed data; F_q : the constant term; $d\hat{\mu}_q, B_\mu$: the distance scale factor and its coefficient matrix; $d\hat{X}_q, B_X$: the coordination estimated value and its coefficient matrix; $d\hat{\epsilon}_q, B_\epsilon$: the deformational parameter estimated value and its coefficient matrix.

From above equation we can get deformational parameters, covariance matrix and variance factor. This mathematical model has following advantages:

(1) To bring deformation parameters into error equations and to do statistical test of significance for parameters were its 2 main features;

(2) By analyzing the reference datum of statistical geodetic network, a conclusion is drawn that it is unfitable to use rank-defected reference datum for the crustal deformation anlysis, and another method is developed to set up different kind of parameter, the classical adjustment and rank-defected adjustment are well unified;

(3) The statistical test theory is applicable for selection of crusted horizontal deformation model.

2.2 The selection of adjustment reference datum of dynamic geodetic network

In the classical adjustment of free geodetic network, general method includes 3 respects:

- (1) to fix the point to determine the position of the network;
- (2) to fix the direction of the side to determine the azimuth of the network;
- (3) to fix the length of the side to determine the scale rate of the network.

But in the rank-defected free adjustment the geometrical center, the average azimuth and average side length of the network were adopted as a datum.

Above adjustment methods must meet following conditions:

- (1) the position datum is stable;
- (2) the azimuth datum is stable;
- (3) the length scale factor is stable.

As has been said before, the free adjustment of dynamic geodetic network in adjustment process of different phase data should meet:

- (1) the position datum should keep stable :

$$\begin{cases} \hat{X}_{gq} = \hat{X}_{g0} = X_g^0 \\ \hat{Y}_{gq} = \hat{Y}_{g0} = Y_g^0 \end{cases} \quad (3)$$

- (2) the azimuth datum should keep stable:

$$\hat{T}_{gq} = \hat{T}_{g0} = T_g^0 \quad (4)$$

- (3) the length scale factor should keep stable:

$$\hat{S}_{gq} = \hat{S}_{g0} = S_g^0 \quad (5)$$

where, g is some adopted datum (E *et al.* 1996).

2.3 Data processing and result analysis

The data processing of deformation monitoring network in the Fildes strait region, West Antarctica was completed by using single point displacement adjustment model. The 0 and 1 points were selected as stable datum (the parameter approximation of these 2 points was adopted from adjustment result of 1988 observable data) and the length scale parameter was set up for observable data, some sides which were not passed through error testing will be deleted from adjustment data. The estimate value of displacement rate (mm/a) and its standard deviation (mm/a) was obtained from adjustment results while parameter testing was completed.

From data analysis of deformation monitoring network in the Fildes strait region, West Antarctica the following conclusions were gained:

(a) Because that there is conspicuous length discrepancy between 1986 data and 1987 (also and 1988) data is found in data processing, its influence on adjustment result must be thought out;

(b) The shear movement and separated movement of Fildes strait fault are not conspicuous;

(c) In opposition to Fildes Peninsula the Penguin Island and Gu Lang Island have been marked with displacement, the move rate is more than 20 mm in a year, but this value is not reliable, so it is important to insist on the observation work of these two islands;

(d) The monitoring the north part of Fildes Peninsula must be strengthened;

(e) There is no evidences of marked displacement in Fildes Peninsula region in a short duration, the long-term monitoring work can be carried on in this region.

3 The processing and analysis of the GPS monitoring data

Since Fildes deformational monitoring network has been set up from 1984 to 1995, except for observed data of three sessions of the network by using DI-20 geodimeter, we obtained observed data of two sessions by using the GPS positioning technique. The first session GPS data was obtained during the 8th CHINARE in the summer of Antarctica, while the other sessions' GPS data was gained during the 11th CHINARE. The instruments are both Trimble 4000SST GPS receiver. By analyzing two sessions' GPS data we can conclude that the noises of the data are tiny. On the average, the first session is 3.70×10^{-6} , while the second is 2.61×10^{-6} , and the qualified percentages of these two date are both 100% (Chen *et al.* 1996).

We can obtain the crustal motion information by processing of the GPS data of the monitoring network that was observed by different sessions. This chapter is trying to study the crustal displacement and strain distribution by using the GPS data mentioned above.

3.1 The principle of monitoring network strain analysis

Assuming that every points are distributed in an even strain field, the strain and analysis can be done on the basis of elasticity theory (Qiu *et al.* 1996a).

In order to derive the relation between the displacement of the net's point and its strain parameters, suppose the coordinates of common point i , which were observed in King George Island respectively in 1992 and 1995 are as follows:

$$X_A = [X_{iA}, Y_{iA}, Z_{iA}]^T, \quad X_B = [X_{iB}, Y_{iB}, Z_{iB}]^T$$

the coordinate difference (or called displacement) of point i is as follows:

$$W_i = \begin{bmatrix} W_{Xi} \\ W_{Yi} \\ W_{Zi} \end{bmatrix} = X_B - X_A = \begin{bmatrix} X_{iB} - X_{iA} \\ Y_{iB} - Y_{iA} \\ Z_{iB} - Z_{iA} \end{bmatrix} \quad (6)$$

From (6), supposing the monitoring area is an even strain field and using least square estimation, the formula of the strain parameters can be expressed as follows:

$$\hat{T} = (A^T P A)^{-1} A^T P L \quad (7)$$

where A is the coefficient matrix, P is the weight matrix, L is the observation vector and T is the strain parameter vector.

From the above two equations we can calculate strain parameters on the basis of the difference of tridimensional coordinate. If Gauss plan coordinates of point are known, the linear strain e_{XX} , e_{YY} , shear strain e_{XY} and rotating strain ϵ can be computed based on the difference of plan coordinate of point. This is:

$$T = [X_0 \quad Y_0 \quad e_{XX} \quad e_{YY} \quad e_{XY} \quad \epsilon]^T \quad (8)$$

The strain parameters that are computed based on difference of plan coordinate have relation with coordinate axes. In practice, there is a pair of special coordinate axes, after deformation, only length on the former axial direction has distortion, the right angle is the same as former. This pair of axes is called principal strain axes. Moreover, one of these axes, the largest strain in every direction of the point, is

called e_1 , the other is the smallest, which is called e_2 , they can be expressed as follows:

$$\begin{cases} e_1 = \frac{e_{XX} + e_{YY}}{2} + r \\ e_2 = \frac{e_{XX} + e_{YY}}{2} - r \end{cases} \quad (9)$$

where $r = \frac{1}{2} \sqrt{(e_{XX} - e_{YY})^2 + 4e_{XY}^2}$

r is general shear quantity, the general strain quantity λ can be computed based on e_1 and e_2 :

$$\lambda = \sqrt{e_1^2 + e_2^2} \quad (10)$$

In the even strain field, general strain λ can be used to describe the even expand and contract of deformation net, ϵ to describe the rotating of net, and general shear to describe the twist of net.

The deformation ellipse of monitoring network can be constituted from e_1 , e_2 and φ , φ is the direction in which the ability to resist system error is the worst, it can be expressed as follows:

$$\text{tg} 2\varphi = \frac{2e_{XY}}{e_{XX} - e_{YY}} \quad (11)$$

3.2 GPS monitoring net displacement and strain analysis

The GPS monitoring net consists of thirteen points. In which, points GW05, GW07 and GW12 are located in the south of Fildes fault, the rest are in the north of the fault.

We have used GPS to observe thirteen points, the first observation was made in 1992, the second was made in 1995. The reference points of two observations are all GW00.

Fildes fault divides monitoring net into south area and north area; area I and II, then point GW00 divides north area into two parts; area II (1) and area II (2).

Since 1986, we have used DI-20 geodimeter to observe monitoring net about three times (1986, 1987, 1988), together with two GPS observations (1992, 1995), many data have been obtained. According to analyzing, two points: GW00 and GW01 in the area of King George Island are steady relatively in this period. On the basis of analyzing we find that scale criterion of GPS observing result in 1992 is different from that in 1995, but the direction criterion observed in two times is the same. So the observing distances in 1995 are all shorter than those in 1992. There are obvious system errors caused by scale criterion error. Therefore, the results observed in two times must be calculated to the same scale criterion and keep the distance between GW00 and GW01 unchanged. United plane coordinate displacements are listed in Table 1, relevant dominating displacements in each area are listed in Table 2.

Table 1. 1995 - 1992 united plane displacement point

P(GW)		01	02	03	04	05	06	07	08	09	10	11	12
ds	ΔX	12	28	3	31	-6	-5	-8	-11	-3	0	-2	-10
/mm	ΔY	12	2	-23	-15	26	9	11	9	-9	-48	-14	24

Table 2. 1995 – 1992 dominating displacement

Area		I	II	II (1)	II (2)
P(GW)		5,7,12	1,2,3,4,6,8,9,10,11	1,6,8	2,3,4,9,10,11
ds	Δ	−8.0	+5.9	−1.3	+9.5
/mm	Δ	+20.3	−8.6	+10.0	−17.8

From Table 1 and Table 2, we see, after united scale criterion, three points GW05, GW07, GW12 in the south of Fildes fault have displaced with the reference points GW00 and the scale criterion of GW00-GW01. Dominating displacements are $\Delta X = -8.0$ mm, $\Delta Y = 20.3$ mm, the displacement direction in area I is opposite to that in area II, relevant displacement values are $\Delta X = -13.9$ mm, $\Delta Y = 28.9$ mm. The relevant displacements in area I and area II (1) are $\Delta X = -6.7$ mm, $\Delta Y = 10.3$ mm, their directions of displacements are the same, but the direction in area II (1) and II (2) are opposite.

Calculated even strain parameters based on displacement are listed in Table 3.

Table 3. 1995 – 1992 strain parameter/ 10^{-6}

e_{xx}	e_{yy}	e_{xy}	ϵ	e_1	e_2	λ	φ
0.803	1.111	−0.943	11.253	1.913	0.001	1.913	130°21'45"

From Table 3, we see, the linear strain of direction after united scale criterion, X is 0.803×10^{-6} , and the linear strain of direction Y is 1.111×10^{-6} . The maximum linear strain is 1.913×10^{-6} , minimum linear strain is 0.001×10^{-6} , shear strain is -0.943×10^{-6} , the maximum linear strain direction is south-east $49^\circ 38'$ (north-west $49^\circ 38'$).

According to two times high precise GPS surveying data, when we regard GW00 point as reference point, and the distance between GW00 and GW01 as scale criterion, the displacement which is caused by relative motion between the south area (area I) and north area (area II (1)) of Fildes fault is about 4.1 mm every year, and which is opposite to GW00 point of which the displacement is about 7 mm each year. There is also some opposing displacement in King George Island area (area II (1) and II (2)). The maximum linear strain is about 0.6×10^{-6} every year, the general strain quantity is about 0.16×10^{-6} every year, and shear strain quantity is about -0.3×10^{-6} ($0.6''$). To sum up, we think there may be some displacements in Fildes fault area, but the displacements are small, and there are also some small shear movement.

Because of the limited condition and time for obtaining monitoring data, the monitoring data of the researches are not enough to analyze this area's crust movement all-sidedly, above analyses are just initial results of this area's crust movement (Qiu *et al.* 1996b).

4 Conclusions

(1) It is a reliable and valid method to monitor the crustal deformation by using GPS high precise positioning technique in Antarctica.

(2) The results of the Fildes deformation monitoring network show that it is absolutely feasible to make the study on the contemporary crustal movement. The emphasis of the study is paid on the figure structure of the network and the rationalization of the data.

(3) We have obtained a large number of data from Fildes deformational monitoring network, which is regarded as an ante-time experimental network in studying feasibility of crustal movement in Antarctica, and the experiment has succeeded. But the covered square of the network is very small, and we only made observation for a short time, so we suggest if we enlarge the network to the South Shetland Islands and the Antarctic Peninsula, we'll get better results.

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