The Reference System in Determining the Parameters of Horizontal Deformations of the Earth's Crust on Geodynamic Polygons

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Abstract*: The article is devoted to the choice of the reference system and the related problem of initial data errors while determining the features of the earth's crustal deformations, determined at the geodynamic polygons (GDP) by the differences of the equalized coordinates of network points between the geodetic measurements epochs. It is shown that the problem is not eliminated in the transition to satellite measuring instruments. In determining the geometric component of the earth's crust deformations, it is recommended to take into account the physical nature of its origin. To ensure the uniformity of the reference system for all geodesic measurements epochs on the local GDPs it is recommended to use the free geodetic networks equalization device without reference points. The deformation components obtained according to the theory of elasticity should be recognized the priority features of the earth's crust deformations on such GDPs.

Keywords: current earth's crust movements, geodynamic polygon, repeated geodetic measurements, deformation features.

I. INTRODUCTION

The study of crustal deformations is a multidisciplinary task related to all earth sciences, as well as to Physics, Mathematics and other fundamental areas of knowledge. Two approaches are used in its solving: physical and geometric [1, 2, 3]. The former determines the physical state of the deformed body (tectonic blocks, separate parts of the earth's crust), internal stresses and load-deformation ratios, while the latter does not taken into account the physical properties of the deformed body but rather analyze the change in its geometry. In practice, these approaches are usually used separately. Thus, the method of repeated geodesic measurements emphasizes the geometric approach to the study of the earth's crust deformations and defines quantitative characteristics of these deformations (change in the body geometry) are determined with the highest possible accuracy. But the earth's crust is, above all, a real physical environment, and the deformation processes occurring in it are caused by physical causes (gigantic temperatures inside the Earth, gravity, inhomogeneity of matter, convection, *etc*.). Therefore, the use of a purely geometric approach to the study of deformations of the earth's crust by geodesists cannot but lead to an ambiguity in the interpretation of the deformation characteristics obtained from the results of repeated geodetic measurements. It is true,_uppermost, for the vectors of horizontal displacements of the DDP network points determined by the differences of the equalized coordinates between measurement epochs and which depend to a large extent on the chosen reference system and the initial data errors [4, 5].

Materials and methods of research: The reference system, used to determine the vectors of horizontal displacements is specified by the starting points for the network equalization. The starting points should be located on stable tectonic structures. Geologists and geophysicists provide land surveyors with information on these structures stability. In this case, it is of fundamental importance that the mutual position of the starting points remains virtually unchanged during all compared epochs of geodetic measurements, and with the accuracy required for geodesy. However, in practice, this condition is not feasible, since the points located on the stable structures indicated by geologists begin to change their mutual position in the course of time and influence the results of equalization, and therefore they influence the vectors of horizontal displacements, according to the scheme of the initial data errors influence, *i.e.* in direct proportion to the distance from these starting points.

In our opinion, this contradiction arises because of a fairly free separation of the geometric and physical approaches to the earth's crust deformations study. Land surveyors focus on its geometric component and forget about the physical nature of the deformation origin, while geologists did not fully take into account the discovery made at the end of the last century in earth sciences [6, 7] about the block-hierarchical structure of the earth's subsoil. According to this discovery widely used in geomechanics [8], mountain ranges and the earth's crust are generally divided into macro-,

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meso-, and microblocks, with the geodynamic processes such as deformations occur in them continuously, but at different speeds: they are slower in macroblocks, and faster – meso- and microblocks. The tectonic structure recommended by geologists as a macroblock can be considered conditionally stable, and geodetic network points can get into meso- and microblocks with a faster manifestation of tectonic processes and change significantly for geodetic accuracy their mutual position.

As a result, there arises a problem of the initial data errors and their influence on the characteristics of the deformations of the earth's crust, uppermost, on the horizontal displacements vectors.

The problem of the initial data errors influence on the characteristics of the modern movements of the earth's crust (MMEC) was studied in detail in processing the results of the ground-dased geodetic measurements on the GDP [4, 9, 10]. The following were considered the characteristics of the earth's crust horizontal deformations:

- differences in sloping ranges;
- vectors of horizontal displacements;
- components of deformations, determined in accordance with the theory of elasticity.

Of these characteristics, we will focus on the horizontal displacement vectors (formulas (1–2)), which are most dependent on the reference system and the original data errors.

$$R_i = \sqrt{\Delta x_i^2 + \Delta y_i^2} \quad (1)$$

$$\alpha_{R_i} = arctg(\frac{\Delta y_i}{\Delta x_i}) \pm 180°, \quad (2)$$

where R_i – the length of the displacement vector at the *i*-th point of the network;

$\Delta x_i, \Delta y_i$ – the difference of equalized coordinates between the two compared epochs of measurements at the *i*-th point of the network;

α_{R_i} – the directional angle of the displacement vector direction at the *i*-th point of the network.

To reduce the impact of initial data errors on the horizontal displacement vectors, Danilov proposed [10] to apply the Helmert transformation, that is, perform the transformation of the coordinates of the 2nd epoch in accordance with formula (3) and determine the displacement vectors using transformed coordinates differences (formulas (4–5)).

$$X_i = a + K_1 x_i - K_2 y_i,$$

$$Y_i = b + K_1 y_i + K_2 x_i, \quad (3)$$

where x_i, y_i – the coordinates of the points in the new system;

X_i, Y_i – coordinates of points in the old system;

a, b, K_1, K_2 – transformation parameters, of which:

a, b – displacement of the beginning of the new coordinate system relative to the old one, respectively, along the X and Y axes.

$$K_1 = m\cos\alpha, \quad K_2 = m\sin\alpha,$$

where m is the change in the scale of the new coordinate system relative to the old one;

α – the rotation angle of the new coordinate system relative to old one.

$$R_i = \sqrt{(x_i' - \overline{X}_i)^2 + (y_i' - \overline{Y}_i)^2}, \quad (4)$$

$$\alpha_{R_i} = arctg\frac{(y_i' - \overline{Y}_i)}{(x_i' - \overline{X}_i)} \pm 180, \quad (5)$$

where x_i', y_i' – the transformed coordinates of the 2nd epoch,

$\overline{X}_i, \overline{Y}_i$ – coordinates of the 1st epoch.

The accuracy of the m_T transformation or the accuracy of inserting the network of a new epoch into the system of stable points of the network of the old epoch is valued by the formula:

$$m_r = \pm\sqrt{\frac{\sum_{i=1}^{r} R_i^2}{r}}, \quad (6)$$

where R_i – values of displacement vectors at stable points, their coordinates were used to determine the transformation parameters; *r* – the number of stable points.

To determine the 4 transformation parameters, it is theoretically sufficient to have 2 points with known coordinates in both compared epochs. Danilov took a larger number of points, and made up an redetermined system of linear equations (3) and determined the transformation parameters using the smallest squares method.

The group of stable points by Danilov, used for calculating the transformation parameters was chosen based on the differences of measured values between the epochs and with geological and geophysical data, which, as a rule, are insufficient for geodetic accuracy. In fact, a different approach to the selection of stable items for determining the transformation parameters can be applied, for example, the combinatorics method. However, it turned out that with this approach, it is possible to obtain several practically equivalent groups of stable items, leading to different transformation parameters and, accordingly, to different vector schemes. Moreover, if we have 3 or more epochs of geodesic measurements on the GDP, we can identify a group

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of stable points, and in comparing the subsequent ones - the other while comparing the first two epochs, both with the Danilov's approach and with the second one. This will eventually result in incompatibility of the obtained vector schemes between all the compared epochs of observations, since the displacement vectors will be assigned to different reference systems.

To solve this problem, we performed an analysis on the possibility of determining the transformation parameters for all points of the network, without dividing them into stable and mobile ones. It turned out that this approach gives more reliable results than the approach of determining transformation parameters for a limited set of network points.

For reliability, we recommend that each case be calculated by the formula (7), the condition in which will ensure that the presence of real displacements at mobile points in the network of the GDP will not affect the accuracy of determining the transformation parameters.

$$\sum_{1}^{m}((X_i^2+Y_i^2)R_i^2) \le 0{,}11\sum_{1}^{n}((X_i^2+Y_i^2)W_i^2), \quad (7)$$

where m – number of mobile points; n – number of all points in the network; X, Y – coordinates of points; R – real (caused by tectonic reasons) bias on mobile points; W – "dislocations" caused by errors in the initial data and random measurement errors.

Calculations with the formula (7), performed for planned networks of Kamchatka GDPs comprising 25 points on average, showed that determining the transformation parameters for all network points is more reliable than finding these parameters according to the Danilov methodology, *i.e.*, on a limited set of stable points due to the малости smallness of real displacements on prognostic polygons. However, it is quite clear that if repeated geodesic measurements on the GDP are performed in order to record the effects of strong earthquakes, the transformation parameters cannot be calculated for all network points, and here Danilov's approach becomes decisive.

To reduce the impact of initial data errors on the horizontal displacements vectors determined from the differences of equalized coordinates, a method based on the theory of equalizing free geodetic networks [9, 11, 12] is also used, which, in our opinion, is more efficient than the previous method. Free geodetic networks are the ones with an insufficient number of source data for their unambiguous fixing in the reference system (the network position relative to the origin of the coordinate system, network scale, orientation).

According to the theory of equalizing free geodesic networks, the solution of a system of normal equations

$$A^T PAX = A^T Pl, \quad (8)$$

where *X* is the vector of unknown parameters (corrections to approximate coordinates); *A* – matrix of coefficients with the unknowns sized $n \times m$; *P* – weighting matrix; *l* – vector of observations, is under the two conditions

$$V^T PV = \min, \qquad X^T X = \min, \quad (9)$$

and it is of the form

$$X = -N^+ L, \quad (10)$$

where N^+ is the pseudoinverse matrix,

$$N^+ = (A^T PA)^+.$$

When processing the planned networks on the GDP, the reference system, relative to which solution (10) is obtained, is specified by the network center, *i.e.* by the average value of the coordinates of the entire network (X*av*., Y*av*.) for the initial epoch.

In practice, the planned network on the GDP is often equalized by the difference of the measured values between the compared cycles [9]. For this case, formulas (8–10) will be rewritten as following

$$N\delta x + L = 0, \quad (11)$$

where δx is the vector of differences of the two epochs coordinates;

N – matrix of normal equations coefficients;

L – free terms matrix.

$$\delta x = -N^+ L \quad (12)$$

N + can be determined by spectral decomposition. Solution (12) is under two conditions

$$V^T PV = \min \text{ and } \delta x^T \delta x = \min, \quad (13)$$

where V is the vector of amendments to the measurement results;

P – weighting measurement matrix.

To assess the accuracy, a well-known technique, based on using a correlation matrix of equalized coordinates differences, is used

$$K_{\delta x} = \mu_0^2 N^+, \quad (14)$$

where μ_0 is the average quadratic error of the weight unit obtained from the equation.

Strictly speaking, the need to fulfill the 2nd of the conditions (13) imposes some restrictions on the real displacement of mobile points, which is not entirely correct. Theoretically, the N + matrix should be determined only by stable points, and the solution should be obtained relative to the coordinate center of stable points. That is, in this case, as well as the use of the transformation method, the issue of choosing stable points arises with all the following problems of the ubiquity in the vector of horizontal displacements definition. Obviously, even in this case, formula (7) may be useful, and if the requirement set out in the formula is met, it is sufficient to obtain the solution for all points of the network.

Modern land surveyors, use the approach of linking local GDP points to IGS (International GNSS Service) network points while performing geodetic measurements on a GDT with satellite methods. In all likelihood, they believe they will manage to avoid the problem of initial data errors if a reference system in the form of points far from the study area and IGS points that are reliable in terms of IGS measurement points is chosen. To this effect, they divide the points of the GDP into long-term and ordinary ones, and perform much longer series of observations at the long-term points. Such an approach was implemented at one of the GDP of NPPs, whose satellite network consists of 17 points and includes 4 long-term ones. Long-term points are related to five points of the IGS network (Fig. 1).

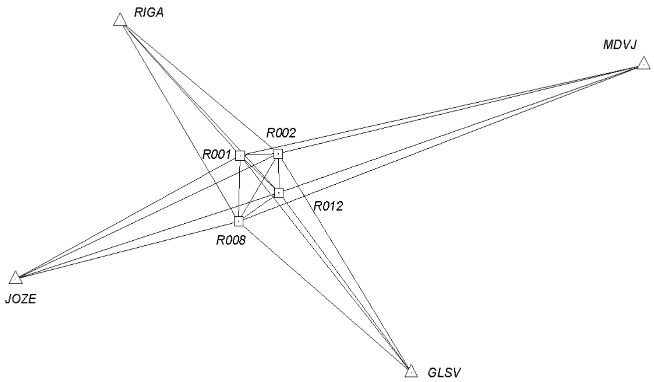


Figure 1 – Linking scheme of 4 long-term items of a nuclear power plant's GDP
(R001, R002, R008, R0012) to IGS network points (RIGA, MDVJ, JOZE, GLSV))

The results of observations at long-term points in both compared epochs are equalized according to the program of long-range satellite networks processing, for example, Bernese [13]. Accordingly, coordinates of the points are different for each epoch. Then, with the obtained coordinates as the source, each epoch is equalized to the applied satellite receivers with the software product, *e.g*. the Trimble business Center; the coordinates of the remaining (ordinary) GDP points and, accordingly, the horizontal displacement vectors, which are usually extremely large, are calculated. Transforming the coordinates by transformation parameters which are determined by the coordinates of two epochs on long-term points hardly improves the result.

The described approach to performing mathematical processing was investigated in [14]. The study showed that it did not justify itself, as it complicated the measurement and mathematical processing methods, which resulted in extremely large displacement vectors, and led to the emergence of a large number of questions, including the problem of initial data errors. It is concluded that the optimal approach to processing networks on local GDPs is the equalization of the used high-precision satellite equipment in the software product without binding to IGS points using the free networks equalization algorithm.

The influence of the reference points choice on the results of repeated geodetic measurements adjustment was also investigated in the article [5], demonstrating the distortion of the results of two cycles of satellite measurements equalization with an increase in the number of points referred to as initial ones, on the sample of the satellite network model.

We have considered another group of horizontal deformations characteristics, which are widely used in the processing of repeated geodetic measurements on local hydraulic GDP [15–18]. The deformation characteristics, called deformation components, are determined in this group by the results of geodetic measurements based on the theory of elasticity by the differences of directly measured geodetic values between the epochs as well as by the differences of the adjusted coordinates. We have dwelt on the more common practice of finding the components of deformations by the differences of adjusted coordinates between the observation epochs.

As is known, in accordance with the theory of differential description of deformations of continuous media, the following characteristics are attributed to the components of deformation: dilatation *Q*, maximum and minimum dilatations *E1*, *E2*, directions of maximum and minimum dilatations *φE1, φE2*, maximum shift *γm* and rotation *w*. They are calculated for each triangle of the geodesic network, taken as a finite_element, on the solution of a system of linear equations (15) using the formulas (17–21).

$$\Delta X_1 = X_1 e_{11} + \quad + a$$

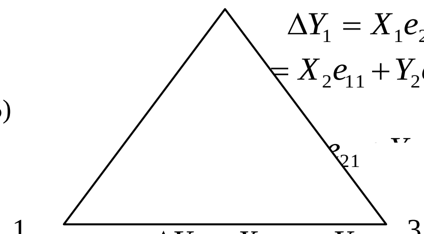
$$\Delta Y_1 = X_1 e_{21} + Y_1 e_{22} + b$$

$$= X_2 e_{11} + Y_2 e_{12} + a$$

(15)

$$e_{21} \quad {}_2 + b$$

$$+ a$$



$$\Delta Y_3 = X_3 e_{21} + Y_3 \ldots$$

where 1–2–3 is the triangle of the geodetic network; a, b – the magnitude of the translational movement along the axes *X*, *Y*; *ΔX, ΔY* – the differences between the coordinates of the network triangle points; *X, Y* – the coordinates of the network triangle points for any of the compared epochs, usually taken for the first one; components of the strain tensor *Tij* (16).

$$\left|T_{ij}\right| = \begin{vmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{vmatrix}, \tag{16}$$

$$Q = \frac{e_{11} + e_{22}}{2}, \tag{17}$$

$$E1 = Q + \frac{1}{2}\sqrt{(e_{11} - e_{22})^2 + (e_{12} + e_{21})^2}, \quad (18)$$

$$E2 = Q - \frac{1}{2}\sqrt{(e_{11} - e_{22})^2 + (e_{12} + e_{21})^2}, \quad (19)$$

$$\gamma_m = E1 - E2 = \sqrt{\gamma_1^2 + \gamma_2^2}, \quad (20)$$

where γ_m is the maximum shift;

$\gamma_1 = (e_{11} - e_{22})$ and $\gamma_2 = (e_{12} + e_{21})$ – shift components.

$$\varphi_{E1,E2} = \frac{1}{2} arctg\left(-\frac{\gamma_2}{\gamma_1}\right) + A^0 \quad (21)$$

The feature of deformation components is that they subject to the errors of the original data in a significantly less degree than the horizontal displacement vectors. According to Esikov N.P. research [15], the shift component of the deformations is completely, and the remaining components are partially, invariant to the reference system.

II. RESULTS AND CONCLUSIONS

The analysis proved that the study of the earth's crust deformations requires a comprehensive approach of specialists from various sciences not only at the stage of the obtained data interpretation, but at all stages of the study. The reliability of determining the earth's crust deformations will significantly increase if the physical nature of its origin will also be taken into account in determining the geometric component of the deformation according to the results of repeated geodetic measurements. The choice of the reference system in determining the quantitative characteristics of deformations, uppermost, the displacement vectors of points, is one of the most crucial stages of the study, since an incorrect reference system will inevitably distort the results of the geodetic network adjustment according to the initial data errors influence scheme, and the degree of reliability of the deformation parameters can lessen gradually. The uniformity of the reference system for all epochs of geodetic measurements on the GDP can be ensured only through the system of equalizing free geodetic networks without any initial points, that is, relative to the network center, defined as the average of the equalized coordinates of this network for the initial epoch. The binding of geodetic networks of local GDPs to IGS network points does not justify itself, since it complicates the processing technique and does not increase the results reliability Since the problem of choosing a reference system remains unsolved in processing the GNSS results of observations on local GDPs, we also recommend to use the system for adjusting free geodetic networks without any initial points.

The components of the earth crust deformation, determined according to the elasticity theory [15], are the least dependent on the reference system and can be recommended as priority ones.

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