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Deformation monitoring surveys of roads and railways

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Abstract — **In this article we evaluated the influence of the error of the reference points on the measurements carried out using polar surveying method with total station for deformation monitoring surveys. The authors present instrumental methods for measuring, processing, analyzing, and interpreting the results based on high accuracy total stations methods for deformation surveys.**

Keywords — deformation survey, road alignment, railway alignment, monitoring, adjustment

INTRODUCTION

The surface and geological structure of the Earth has been slowly changing for many years under the influence of endogenous and exogenous forces. The leading role of endogenous processes is earthquakes, volcanoes, and movements of the Earth's crust. These forces, especially the vertical movements of the Earth's crust, create contrast in relief. Together with exogenous processes-landslides, erosion, settlements, etc., events with destructive effects have been formed.

Engineering facilities and buildings, roads, and railways, as well as the terrain around them, are subject to deformation by various factors. The deformation processes differ significantly in terms of mechanism, type, scope, duration, dynamics, consequences for buildings and structures. In the study of deformations, different methods are used and appropriate methods for determining horizontal and vertical displacements are employed. In addition, spatial (three-dimensional) and combined methods for determining spatial displacements are used. Horizontal displacements are determined by triangulation, trilateration, triangulateration networks, traverse method, alignment method, etc. Differential, trigonometric, hydrostatic levelling, micro leveling, etc., are used to determine the vertical deformation, depending on the required accuracy and structural features and the possibility of access to the objects of study. Spatial displacements are determined by three-dimensional methods, 3D networks, GPS, photogrammetry, laser scanners, etc. Geodetic instruments for determining deformations include levels, total stations, GPS receivers and more. Geotechnical instruments include extensometers, inclinometers, piezometers, accelerometers, etc. The geodetic and geotechnical tools mentioned are also used in various combinations with each other-e.g. the movements of the Earth's surface are determined by geodetic measurements and the deep movements by geotechnical measurements. Another example is in the field of geotechnics, where precise leveling or clock indicators are used for static testing of pilots to detect deformations. The latter is also used to track the evacuation of columns of buildings. A deformation monitoring survey usually consists of several different types of surveying, using different types of geodetic instruments combination and this process is on the basis of the so-called integrated surveying concept. Among the instrumental methods for the study of geotechnical phenomena, geodetic and geotechnical (semi-geodetic) methods are one of the most used. The use of instrumental methods implies the establishment of a special methodology and system for measuring, processing, analyzing, and interpreting results. It is important that the number of points is optimal. When organizing the measurements for the deformation survey, the design, purpose, features of the building or facility shall be taken into account. All plans and studies made so far are used. The way to stabilize points and benchmarks, the instruments with which the measurements will be made, and the sequence of measurements must be specified. The points K_i, I_i are reference points (stable points) (Fig.1) and (Fig.2). The points N_i are object points. In this case points N_i are monitored points of the dam. The points O_i are the orientation points.

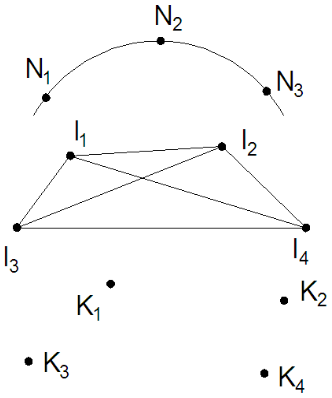

Figure 1 Stable and object points

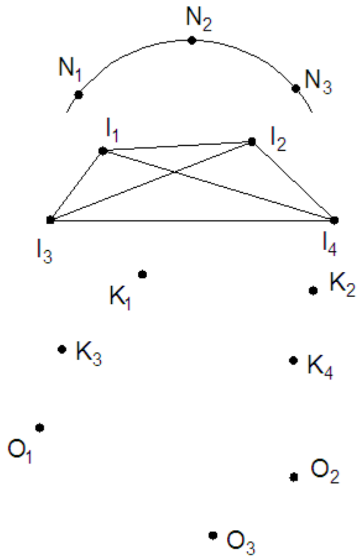

Figure 2 Orientation, stable and object points

The changes that occur in the position of the points between the individual measurements at accepted intervals of time are affected by the deformation process. The reconstruction and control of the railways and roads is impossible without the creation of a geodetic network close to them. The construction of the geodetic network can be carried out only by GPS, or only with a total station. If we build a geodetic network only using GPS technology, the measurement time will be unacceptably long. The price of determining the position of a single point with GPS is high, which can make projects more expensive. Building a geodetic network only with a total station, we automatically increase the number of points, and the number of measurements. The best variant for network design is open traverse, at which the 2 first and 2 endpoints are measured by GPS, and to find the coordinates of the intermediate points, measurements are made with the total station. From this network deformation surveys are geometry checks of the railway axis with angle and distance from the nearest station of the geodetic network to the points of the road (railway) digital model. The deformation of road and railways are most often associated with landslides, mining, salt deposits near them, etc. During construction works of roads and railways is necessary to monitor the deformation of unstable terrain and control of alignment geometry. Mobile measurement platforms are the most used methods, and applied measurement techniques are also mobile satellite measurements. The track geometry components as alignment, cant and gauge are measured directly with trolleys and recorded in real-time. The deviation between the design and the measured position of the railway makes it possible to assess the quality of the geometry of the route.

I. LEAST SQUARES ADJUSTMENT

Least squares adjustment helps us to remove the discrepancies in the geometric conditions of the geodetic networks, to estimate the accuracy of measurements, coordinates, etc., calculated after the adjustment. With the help of adjustment, we increase the accuracy of the measured quantities and their functions and perform the verification of the quality of the measurements. The equation of least squares estimation is given by:

$$v = Ax - l \tag{1}$$

where l (the vector of absolute terms) and v are m–dimensional vectors and x is an n–dimensional vector. The matrix A is a so-called design matrix and v is the noise vector. We seek the solution x satisfying the criterion of least squares $v^T Pv$ = min, where P is the weight matrix. The unknowns x with minimum variance are computed using the next formula [1]:

$$x = (A^T PA)^{-1} A^T Pl \tag{2}$$

The cofactor matrix QX is achieved by the formula:

$$Q_X = (A^T PA)^{-1} \tag{3}$$

The covariance matrix by the formula:

$$C_X = \sigma_0^2 (A^T PA)^{-1} \tag{4}$$

and root square mean error of unknowns are computed as standard deviations of the adjusted quantities:

$$m_X = \sigma_0 \sqrt{Q_X} \tag{5}$$

where the variance of unit weight (variance factor) is calculated using:

$$\sigma_0 = \sqrt{\frac{v^T Pv}{n-u}} \tag{6}$$

or

$$\sigma_0 = \sqrt{\frac{v^T Pv}{s}} \tag{7}$$

with n-number of observations, u-number of unknowns and **s=n-u** is the degree of freedom (redundancy).

The major semi axis **a** and the small semi axis **b** of the standard error ellipse (Fig.3) are given by the formulas presented in [2]. For a single point **P** mean square error $\boldsymbol{m_p}$ can be expressed knowing mean square error $\boldsymbol{m_x}$ and $\boldsymbol{m_y}$ of x and y axis and major a and minor b semi axis of the error ellipse (8).

$$m_P = \sqrt{m_x^2 + m_y^2} = \sqrt{a^2 + b^2} \tag{8}$$

II. Deformation monitoring surveys of roads and railways

The horizontal alignment of the roads consists of straight lines, spiral curves, circular arcs, etc., and coordinates of the points from road and rail alignment are known. The measurement accuracy depends on the minimum deformations to be recorded, the expected size, the speed of movement, the existing manuals, etc. The chosen method is used without changes from the beginning to the end of deformation measurements and the accuracy of the measurements in the individual epochs must be the same. The reference points and benchmarks from which the movements of the object points and benchmarks from the deforming zone are determined should be checked to see that they have not changed their initial position. The assessment of the stability of the reference points and benchmarks may be made for a single point, or for the reference network, either directly from the measurements or by adjustment. Additional information for the assessment of railway and road accidents, e.g. place of derails in straight lines, curves, etc., is necessary for the expertise [3]. Changes in the straight part and curves can be detected by the GNSS method. Mobile measurement platforms are the most used methods [4]. GNSS measurements of the railway are usually carried out using the RTK method. The different communication protocols used for RTK positioning are presented in detail in [5].

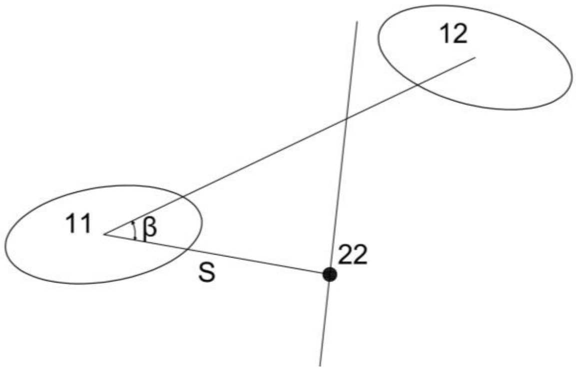

Figure 4 Deformation monitoring point

Using the formula (9) given in [6] we may calculate mean square error of the sample point 22 from horizontal alignment for measurements carried out using polar surveying method (Fig.4).

$$m_{22} = \sqrt{m_S^2 + \frac{m_\beta^2}{\rho^2} S^2 + m_{11,12}^2 + m_{FIX}^2} \tag{9}$$

where

m_{22} – mean square error of the point 22

ρ=63,6620^g

$m_{11,12}$ – is the effect of the mean square errors of the reference points (11 and 12)

m_β – mean square error of the measured angle

m_S – mean square error of the measured distance

m_{FIX} – error of the fixing of the point from road or rail alignment on the terrain

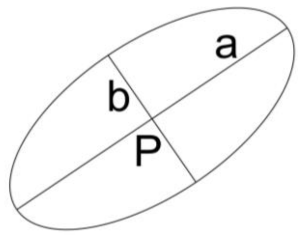

Figure 3 Error ellipse

In the basis of this formula are fundamental relations for the measurements using polar surveying method:

$$X_{22} = X_{11} + S\cos\beta \tag{10}$$

$$Y_{22} = Y_{11} + S\sin\beta \tag{11}$$

$$m_{X,22} = \sqrt{\left(\frac{\partial f}{\partial x_{11}}\right)^2 m_{X,11}^2 + \left(\frac{\partial f}{\partial S}\right)^2 m_S^2 + \left(\frac{\partial f}{\partial \beta}\right)^2 \left(\frac{m_\beta}{\rho}\right)^2} \tag{12}$$

$$m_{Y,22} = \sqrt{\left(\frac{\partial f}{\partial y_{11}}\right)^2 m_{Y,11}^2 + \left(\frac{\partial f}{\partial S}\right)^2 m_S^2 + \left(\frac{\partial f}{\partial \beta}\right)^2 \left(\frac{m_\beta}{\rho}\right)^2} \tag{13}$$

or

$$m_{X,22}^2 = m_{X_{11}}^2 + (\cos\beta)^2 m_S^2 + (-S\sin\beta)^2 \left(\frac{m_\beta}{\rho}\right)^2 \tag{14}$$

$$m_{Y,22}^2 = m_{Y_{11}}^2 + (\sin\beta)^2 m_S^2 + (S\cos\beta)^2 \left(\frac{m_\beta}{\rho}\right)^2 \tag{15}$$

Adding the expressions (14) and (15) we get the same formula as formula (9) for root mean square error. After taking the account of the mean square error of second reference point 12, the mean square errors for axis x and y of the point 22 from first $m_{X,22}^I$, $m_{Y,22}^I$ and second epoch $m_{X,22}^{II}$, $m_{Y,22}^{II}$, are calculated by propagating errors in the reference points, measured angle and distance:

$$m_{X,22} = \sqrt{m_{X_{11}}^2 + m_{X_{12}}^2 + (\cos\beta)^2 m_S^2 + (-S\sin\beta)^2 \left(\frac{m_\beta}{\rho}\right)^2} \tag{16}$$

$$m_{Y,22} = \sqrt{m_{Y_{11}}^2 + m_{Y_{12}}^2 + (\sin\beta)^2 m_S^2 + (S\cos\beta)^2 \left(\frac{m_\beta}{\rho}\right)^2} \tag{17}$$

For the purpose of deformation monitoring surveys we need the displacement vector ***d*** between two epochs and error of the displacement vector m_d. The displacement vector is found from coordinate differences according to formulas (18), (19) and (20). The error of the displacement vector is calculated using mean square errors of first and second epoch deformation surveys (21), [7].

$$\Delta X = X_{22}^{II} - X_{22}^{I} \tag{18}$$

$$\Delta Y = Y_{22}^{II} - Y_{22}^{I} \tag{19}$$

$$d = \sqrt{\Delta X^2 + \Delta Y^2} \tag{20}$$

$$m_d^2 = (m_{\Delta X}^2 + m_{\Delta Y}^2)/2 \tag{21}$$

where

$$m_{\Delta X}^2 = (m_{X,22}^{I})^2 + (m_{X,22}^{II})^2 \tag{22}$$

$$m_{\Delta Y}^2 = (m_{Y,22}^{I})^2 + (m_{Y,22}^{II})^2 \tag{23}$$

The ratio greater than 2.0 is the test statistic whether significant movements of the points has been occurred at the 95% confidence level [7].

$$\frac{d}{m_d} > 2.0 \tag{24}$$

III. Experiment Analysis

Let us consider a sample point from road or railway axis – p.22 to be monitored for displacements with d=30mm. According to the theory of least squares adjustment [8] to avoid influence of the error of the reference points 11 and 12, mean square error of the points $m_{X,11}$ and $m_{X,12}$, should be one-third smaller than $m_{X,22}$ and $m_{Y,11}$, $m_{Y,12}$, should be one-third smaller than $m_{Y,22}$ (16) and (17). In our experiment we show that if $m_{X,11}$, $m_{Y,11}$, $m_{X,12}$, $m_{Y,12}$ are $\sqrt{2}$ smaller (instead of one-third smaller) of the mean square error of the $m_{X,22}$ and $m_{Y,22}$, the derived displacements are significant at the 95% confidence level if appropriate surveying measuring technology is chosen. For given $m_{X,11}$=6 mm, $m_{Y,11}$=7 mm, $m_{X,12}$=5 mm, $m_{Y,12}$=7 mm, m_S =5 mm; m_β =10^{cc}, S=150.002 m, β =38,1418^g and applying the formulas (16) and (17) the resulting mean square errors are: $m_{X,22}^{I}$=9 mm, $m_{Y,22}^{I}$ =11 mm, $m_{X,22}^{II}$=9 mm, $m_{Y,22}^{II}$ =11 mm and d/md = 2.1, which means that the significant movement of the point 22 has been occurred at the 95% confidence level.

IV. Conclusions

Deformation surveys can be performed with total stations in zones where GPS cannot be used, where there is no line of sight to the satellites, e.g. cities, subway, tunnels, etc. Total stations provide better precision than GPS for short distances, and may achieve millimeter accuracy. In the current study, the influence of the error of the reference points on the measurements carried out using the polar surveying method with a total station has been analyzed. The estimation of the displacements of the monitored points can be established even if the mean square error of the reference points is $\sqrt{2}$ smaller than the mean square error of the monitored point. The approach used has been practically verified by the authors to detect deformations of the points of the railway line between two railway stations.

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