ANALYSIS OF DEFORMATION SURVEYS IN GEOTECHNICAL ENGINEERING: THE CONCEPTS

Roumen A. Ivanov, Nevena I. Babunska-Ivanova
e-mail: rang75@hotmail.com

ABSTRACT
Monitoring and the analysis of the results from deformation surveys are important due to the risk of landslides, structural movements, stability assessments of buildings, etc. The report reviews methods for finding stable points in geodetic networks. This research is concerned with the implementation in practice of the standards for deformation analysis and the number of reference points. The background for the analysis of the stability of points is presented together with the various criteria used in deformation analysis. The process for the detection of unstable reference points and the minimum number of reference points in deformation surveys are analyzed.

1. Theory of deformation analysis

Measurements of deformations by surveying methods are of primary importance due to the risk of landslides, structural movements, stability assessments of buildings, etc. Analysis of deformation measurements may be made by using robust and non-robust methods, invariant (angle differences, distance differences, etc) and non-invariant methods. The displacements of points can be obtained directly from measurements or after the adjustment. In the geodetic practice of stable point deformation analysis, the following known methods are used – the Karpenko method, the Runov method, the Ganishin method, the Storozhenko method, the Costachel method, the Botyan method, the Martuszewicz method, the Marchak method and the Chernikov method. Several of those methods have been examined and a comparative analysis has been made [3]. The Costachel method is based on the principle of marking the most stable benchmark of the network. This method uses a free leveling network. The author (Costachel, A.,) proposed that the benchmark for which the sum of the height difference is minimal [vv] = min is the "most stable", and its height from the first epoch should be taken as the initial when calculating the heights of other benchmarks in the current observation epoch. An example of this method has been presented in [21]. Applied to constrained adjustment, for this method, the selected datum is the one that minimizes the sum of deformations (displacements). The Chernikov method is based on the principle of constant average height network benchmarks. The Botyan method is almost the same as the Costachel method. In this method, the benchmark with [vv]=max is removed from the reference points of the network. For the Martuszewicz method, the most stable point is the point that fulfills the condition [|v|]=min. The concepts and applied methods for accessing point stability should be multi-criteria. An example of geotechnical engineering multi-criteria methods are the methods to analyze slope stability and critical slip surface – Fellenius, Bishop, Janbu, Spencer, Morgenstern & Price, etc. Similarly, the concept of multi-criteria methods can be applied to deformation analysis. Free or constrained network adjustment is used for deformation surveys [4]. A central part of the methods of deformation analysis is the Hanover School (global congruency test) [25] and the Fredericton School (Iterative Weighted Similarity Transformation-IWST) [12,13]. The global congruency test is often used for the detection of deformations and the stability analysis of reference points. The core of the global congruency test is the test statistic:

$$\frac{dx^T Q_d^+ dx}{h\sigma_0^2} \approx F_{h,s,\alpha} \tag{1}$$

where dx are the displacements, with their cofactor matrix Qd, σ_0 is the pooled variance factor, Q_d^+ -pseudo-inverse matrix, α - significant level, h - rank of the cofactor matrix, s - sum of degrees of freedom for first and second adjustment.

- Chen-Chrzanowski-Secord method

Originally developed by a group of scientists from the University of New Brunswick, the Chen-Chrzanowski-Secord method (IWST method) is one of the most used classical tests in deformation analysis. The procedure for the detection of deformations with the IWST processing algorithm [10,11,31] has the following next steps: Computation of the displacement vector dx with its cofactor matrix Qd. In the beginning, the weight matrix (W) is accepted as $W^0 = I$. After applying S-transformations the displacement vector (2) for k and k+1 iterations is estimated.

$$d_{k+1} = [I - G(G^T W_k G)^{-1} G^T W_k] d_k = S_k d_k \tag{2}$$

The displacement weight matrix W is changed to be:

$$W_{k+1} = diag[1/(\left| d_k \right| + c)] \tag{3}$$

where **c** is a small constant (e.g. c=0.0001)
The iterative process starts and stops when $\left| d_{k+1} - d_k \right| < 0.01$mm, followed by transformation:

$$Q_d = S Q_d S^T \tag{4}$$

The final step is checking the stability of network points using a single point test (similar to a global congruency test). The following notation is used: I = identity matrix; k = number of iterations; d = displacement vector for k and k+1 iterations; S = transformation matrix; W = displacement weight matrix; G = inner constraint matrix. The IWST condition is [|d|]=min.

- Pelzer-Niemeier method

The Pelzer-Niemeier method (Hanover method) uses the global congruency test mentioned above. Implemented in deformation analysis software, it indicates the presence of statistically significant deformations in the monitored free networks. The term congruency test, with appropriate definition was introduced by W. Niemeier in 1981 [26]. This test is the first step in the deformation analysis process. An explanation for the localization of the deformations is presented in [18]. The displacement vector is divided into two subvectors, representing other points and deformed points, respectively (5).

$$d = \begin{bmatrix} d_F \\ d_B \end{bmatrix} \tag{5}$$

The cofactor matrix is divided into sub-matrices (6).

$$Q_d^+ = \begin{bmatrix} P_{FF} & P_{FB} \\ P_{BF} & P_{BB} \end{bmatrix} \tag{6}$$

A global test statistic R_B is calculated based on a quadratic form:

$$R_B = \overline{d_B^T} P_{BB} \overline{d_B} \tag{7}$$

where,

$$\overline{d_B} = d_B + P_{BB}^{-1} P_{BF} d_F \quad (8)$$

The point that contributes the maximum R_B is accepted as a deformed point. To prevent datum effects on the global congruency test, the displacements and their corresponding covariance matrices are transformed into new datum using S-transformation. Finally, a single point test is carried out. More about this method can be found in [26,27,28]. For the study of deformations, different instrumental methods are used. New communication technology enables a connection between monitored objects and instruments over a long distance, to transfer measurements and share data between organizations [19]. Changes in the position of points from two or more measurement epochs over a period give us the size and direction of the displacements. For deformation surveys we need the displacement vector **d** between two epochs and the mean square error of the displacement vector m_d. The displacement vector is found from the coordinate differences. The displacement vector's mean square error is calculated using the mean square errors of the first and second epoch deformation surveys. The ratio greater than 2.0 is the test statistic for whether significant movements of the points have occurred at the 95% confidence level [9].

$$\frac{d}{m_d} > 2.0 \quad (9)$$

The displacement analysis for the verification of the stability of the reference stations can also be done with a relative error ellipse and the displacement vector (Fig.1).

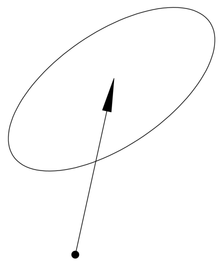

Fig.1 Displacement analysis with a relative error ellipse

2. Monitoring of natural and man-made objects

The deformation monitoring network consists of reference points and object points. Methodology related to the design of deformation networks is an important aspect of the studies, especially the number of reference points. Having a minimal number of reference points is a key concept for the design of deformation monitoring networks and deformation analysis. Although there are manuals that define the minimum number of reference points e.g. US Army Corps of Engineers [15], there is a need to review them in the context of the design of new deformation monitoring surveys in the EU. The implementation of modern methods for the evaluation of point stability must be made with EUROCODE standard. Thus, EU needs a new EUROCODE standard dealing with point stability analysis. In the deformation analysis strategy, the identification of stable points and the minimum number of stable reference points are important to be defined in manuals. For example, for two-dimensional networks we must have at least three (preferably four) or more stable reference points [25]. The optimal network design for GNSS should use three points in the stable zone with the possibility that those three points can be controlled from points placed near buildings, stable terrains or from high-precision networks for a short period of time. The number of reference points (stable points) may be different for each GPS landslide survey project, and in realized projects designed for these purposes, two points are located in geologically stable terrain [2,35], three points [29,30], and six points [14]. The analysis of slope stability involves potential failure surface, calculating the factor of safety with equations such as those presented in [22]. In [23] the article describes the different types of strengthening facilities used to reduce erosion in mountainous terrain. It is important to consider the effects that these protection systems may have on ecology, as some protection systems may have unintended consequences for ecology [1]. To determine the potential danger of a landslide, it is necessary to make a detailed structural analysis of the massif [20]. There are many examples of mine collapses and damage caused by different factors. GNSS measurements for deformation monitoring of mines are of great importance. The methodology of the GNSS method assisted with UAV photogrammetry effectively determines the main factors causing slope failures [17]. In [34] authors describe a modern deformation monitoring concept that uses Ground-Based SAR for open-pit mine surveys. In [7] the authors present the application of InSAR and GNSS for landlide monitoring. Laser scanners are applied intensively for deformation monitoring applications [5,24]. Laser scanners have a great advantage over other instruments because they record high-density spatial data. In practice, the deformation surface is modeled instead of defining the deformation by comparing individual measured points [36]. Research on the use of laser scanning for applications in underground mining has been presented in [32]. The design and implementation of modern geotechnical equipment applied for dam monitoring may be found in [6]. An analysis of deformation measurements in mine surveying may be made by using the approach presented in [8]. Strain analysis includes the calculation of the deformation parameters and elements of the symmetric tensor, the analysis of dilatation, total shear, etc.,[16,33].

Conclusions

To find stable points in geodetic networks, several methods can be used, which leads to the concept of complex deformation analysis (CODA). The theoretical background for the analysis of the stability of points is presented, along with the various criteria used in deformation analysis. The EU needs a new EUROCODE standard dealing with point stability analysis and the minimum number of reference points. The concepts and applied methods for accessing point stability should be multi-criteria. It is of great importance to name deformation analysis methods after their inventors, focusing on the pioneering scientists who have contributed to the field of deformation surveys.

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