Sborník vědeckých prací Vysoké školy báňské – Technické univerzity Ostrava
Řada hornicko-geologická
Volume L (2004), No.2, p. 1-10, ISSN 0474-8476

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DEFORMATION MEASUREMENTS ON BULK DAM OF WATERWORK IN EAST SLOVAKIA

DEFORMAČNÉ MERANIA NA SYPANEJ HRÁDZI VODNÉHO DIELA NA VÝCHODNOM SLOVENSKU

Abstract

The paper discusses some geodetic terrestrial positional measurement results within frame of deformation survey of bulk dam of the waterwork Pod Bukovcom in East Slovakia in vicinity of the town of Košice. Periodic yearly measurements of terrestrial position and yearly leveling measurements have been realized since 1999. Testing and confirming measurements by GPS navigation surveying (GPS) have been equally made since 2001 only to take into consideration a potential survey of bulk dam deformation by means of such satellite system.

Independent results of analytical as well as graphic analysis procedures confirmed the assumption that the object points and thus the dam did indicate with 95 % certainty any statistically significant movements. Confidence ellipses of some points did not comply with null hypothesis, because the deformation vectors exceed these confidence ellipses. However, despite this fact the overlapping of the confidence ellipses by deformation vectors was negligible and in view of this deduction about stability of the points was accepted.

Abstrakt

Článok prezentuje niektoré výsledky geodetických terestrických polohových meraní v rámci deformačného šetrenia sypanej hrádze vodného diela Pod Bukovcom neďaleko Košíc vo východoslovenskom regióne. Periodické každoročné terestrické polohové a výškové merania sú na hrádzi realizované od roku 1999. Od roku 2001 sú na sypanej hrádzi tiež aplikované družicové navigačné merania (GPS – Globálny polohový systém) len pre posúdenie možnosti deformačného šetrenia týmto družicovým navigačným systémom.

Nezávislé výsledky analytických a analyticko-grafických analýz potvrdili predpoklad, že objektové body a tým aj hrádza nedoznali akékoľvek štatisticky významné pohyby s určitosťou na 95 %. Konfidenčné elipsy niektorých bodov nesplňali nulovú hypotézu, pretože deformačný vektor presahoval tieto konfidenčné elipsy. I napriek tejto skutočnosti presahovanie konfidenčných elíps deformačnými vektormi je zanedbateľné a z tohto aspektu je akceptovaná dedukcia o stabilite týchto bodov.

Key words: bulk dam, terrestrial positional measurement, leveling, graphic analysis, deformation testing, confidence ellipse, test statistics.

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Introduction

Movements and deformation effects on building objects and structures due to own weight, water pressure, inner temperature, contraction, atmospheric temperature and earth consolidation occur. It is necessary to investigate such deformation effects and movements according to philosophy that “All is in continuous movement”. Especially, it is necessary to embark on monitoring and analysing of deformation effects and movements of any sizeable human building work. The dams rank among major waterworks on which monitoring of deformation and movement necessarily has to be done.

The bulk dam Pod Bukovcom has been built up on the river Idan between municipalities Bukovec and Malá Ida in East Slovakia. The fagot bulk dam is situated in a morphologically very advantageous profile in place of the old approximately 7 m high fagot dam which was liquidated after erection of the today up-to-date fagot dam. The purposes of the last-mentioned dam are to supply industrial water for cooling up of metallurgical blast furnace equipment of company US Steel Košice in case of its emergency. The water basin formed by the dam should also equalize floodwater and it is used for recreation during summer time.

The algorithm of detection of deformity

Detecting of deformation effects is based on the existing procedural technique, which is called algorithm (*Fig.1*). It results from the diagram in *Fig.1* that a complete procedure, which starts by project trough measurement is terminated by an analysis of gained adjustment results. The processed results are analysed in view of geometrical or physical properties of the examined object.

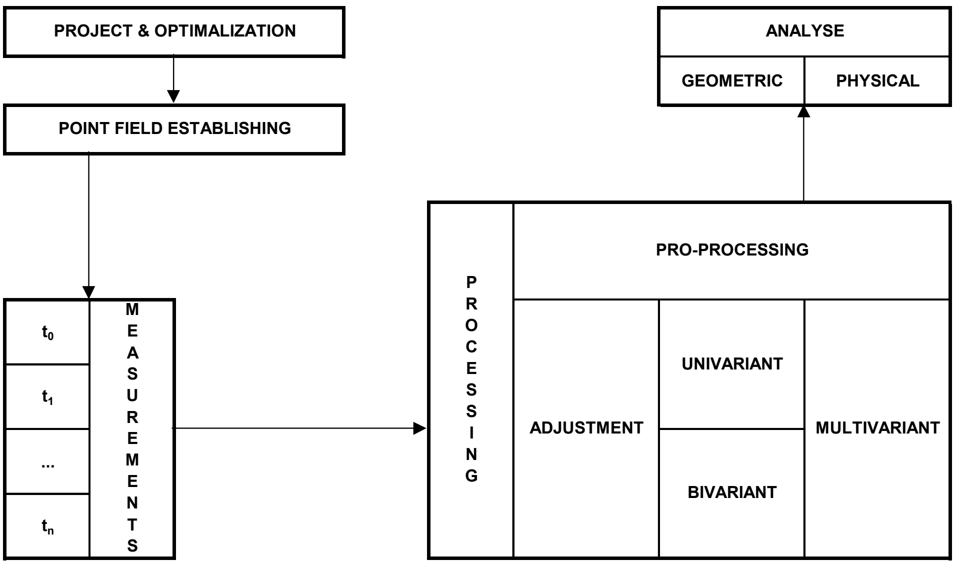

Fig. 1: Scheme of algorithm of detection of deformation.

Network of bulk dam Pod Bukovcom

Six reference points have been stabilized outside the fagot bulk dam. The reference points were situated in distances of about 50-100 m from the dam (Technical bases, 1965-98). The reference points were labelled A1 through F1. These points substituted the old reference points on which measurements were carried-out since 1985. Stabilizing of the reference points is safeguarded by breasting pillars with a thread for exact forced centring by means of surveying equipment (TC Leica 605 L and Zeiss Koni 002).

The object points on the fagot bulk dam are arranged so as to represent the fagot dam geometry and the assumed best values of pressure on the fagot dam at certain water level. The points are situated in six profiles on the fagot dam. As the object points should indicate and so transmit any fagot dam deformation effects, they had to be stabilised approximately to a depth of 1.8 m. Generally, there are 26 object points fixed on the fagot dam (*Fig.2*). Two of them have been destroyed.

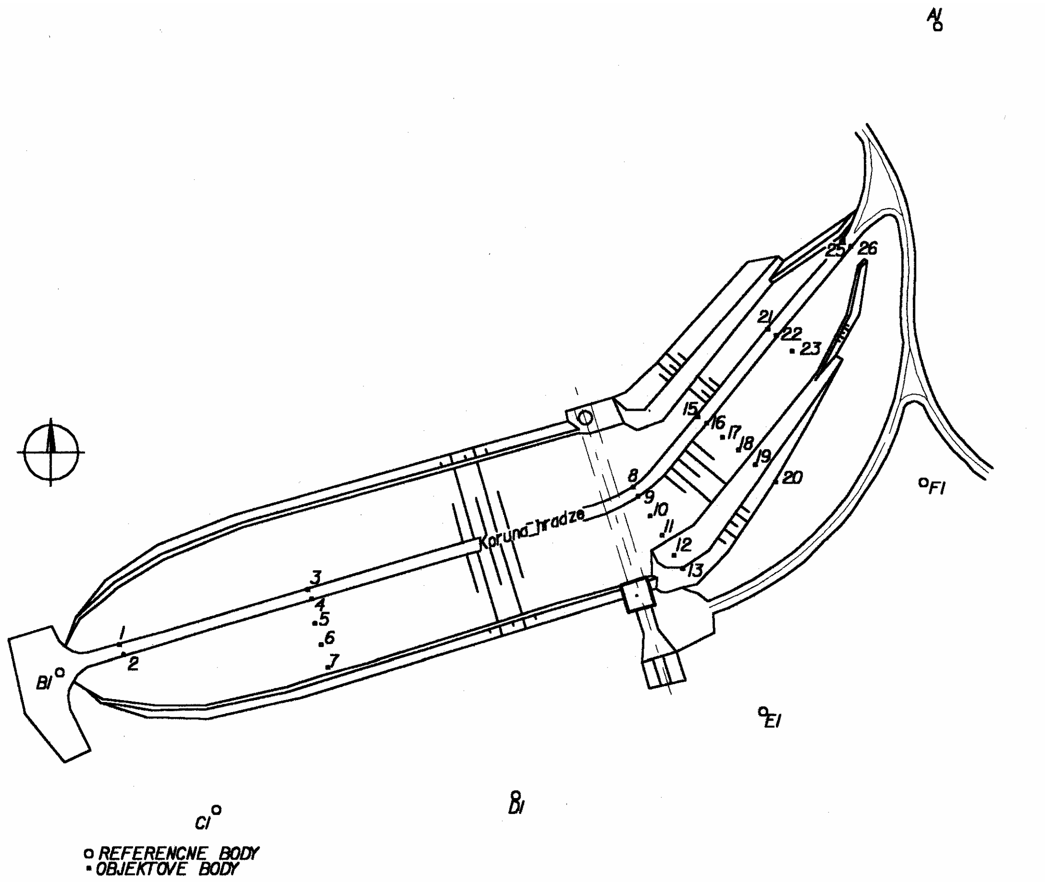

Fig. 2: Network of field of points arranged on the fagot bulk dam Pod Bukovcom, (1:5 000 scale);
○ *reference points,* ● *object points.*

Analysing of detection of deformation

Analysis of deformation network processed data can be done by means of analytic or graphic methods. It depends on means, which are used middles for network congruence. The methods applied differ one from another according to resultant shape of results for their presentation. However, from the point of view of deduction analysis the results of presentation shall be equivalent.

From the point of view of congruence testing the analyses are structured into the following techniques:

- statistical,
- deterministic.

The congruence method of geodetic networks follows on from the basis of examination and analysis of positional co-ordinates from particular periods (epochs).

From the point of view of tested values the methods of analysing of deformation detection can be structured into:

- parametric methods,
- non-parametric methods.

The parametric testing methods make use of co-ordinate differences of tested points, while the non-parametric methods test the invariant differences of network elements. Values of network structures are obtained by means of an estimation model *LSM* (last square method) or by means of robust statistical models.

The statistical testing techniques are most frequently used for the purpose of congruence testing deformation networks. The task of such testing is to decide, whether a network co-ordinate or invariant differences are statistically meaningful or not. It is necessary for this purpose to form a null hypothesis the form of which is follows (Böhm 1990, Kubáčeková et al. 1982, Sedlák 1996, Kožarík 2000, Ječný 2001)

$$H_0 : E(\hat{\boldsymbol{C}}^1) = E(\hat{\boldsymbol{C}}^2) \tag{1}$$

or respectively

$$H_0 : E(\boldsymbol{L}^1) = E(\boldsymbol{L}^2)\ , \tag{2}$$

where $\hat{\boldsymbol{C}}^i$ is vector of the adjusted co-ordinates of object points within epoch i, $\boldsymbol{L}^i$ is vector of the measured values during epoch i.

It means that mean values of vector of adjusted co-ordinates of measuring values from the first epoch are equalized to mean values of vector of adjusted co-ordinates or to measuring values from the second epoch.

For the co-ordinate differences $\delta\hat{\boldsymbol{C}}^i$ the following equation is valid

$$H_0 : E(\delta\hat{\boldsymbol{C}}^1) = E(\delta\hat{\boldsymbol{C}}^2)\ . \tag{3}$$

The output register for the adjusted co-ordinates of object points is in admissible form as follows

$$\hat{\boldsymbol{C}}^1 - \hat{\boldsymbol{C}}^2 = 0\ . \tag{4}$$

For the null hypothesis H_0 the equation is equally used in the form of

$$H_0 : H.\boldsymbol{\Theta} = \boldsymbol{h}\ , \tag{5}$$

where $\boldsymbol{h}$ is null vector, $\boldsymbol{\Theta}$ is matrix of the estimate parameters.

The test statistics T is compared with the null hypothesis. The universal test statistics is based most frequently on the tested value and mean error s ratio

$$T = \frac{\left|\delta\hat{\boldsymbol{C}}\right|}{s.\delta\hat{\boldsymbol{C}}}\ . \tag{6}$$

The null hypothesis H_0: $H.\boldsymbol{\Theta} = 0$ is formulated for co-ordinate differences vector. According to this the test statistics T will be in form of

$$T = \frac{\dfrac{\delta\boldsymbol{C}^T.\boldsymbol{Q}_{\delta C}^{1}.\delta\boldsymbol{C}}{k}}{\dfrac{\boldsymbol{v}^T.\boldsymbol{Q}_L^{1}.\boldsymbol{v}}{f}}\ , \tag{7}$$

where $\boldsymbol{Q}$ is deformation vector matrix, $\boldsymbol{v}$ is vector of corrections.

The quadratic form of co-ordinate divergences is in numerator and the empirical variation factor s_0 is in denominator. The form of test statistics after having been arranged is as follows

$$T = \frac{\delta\boldsymbol{C}^T.\boldsymbol{Q}_{\delta C}^{1}.\delta\boldsymbol{C}}{k.s_0^2} \approx F(1-\alpha, f_1, f_2)\ , \tag{8}$$

where $1-\alpha$ is reliability coefficient, α is confidence level (95% or 99%), f_1, f_2 are degrees of freedom of F distribution (Fischer's distribution) of accidental variable T, k is number of co-ordinates accessing to network adjustment.

The degrees of freedom are selected according to type of adjustment. For free adjustment the following equations are valid

$$f_1 = n - k + d\ , \quad f_2 = k - d \tag{9}$$

and for bonding adjustment

$$f_1 = n - k\ , \qquad f_2 = k\ , \tag{10}$$

where n is number of measuring values being entered into network adjustment, d is the network defect at free adjustment of network.

The test statistics T should be the subject to comparison with the critical test statistics T_{CRIT}. T_{CRIT} can be found in tables of F distribution according to degrees of freedom of network.

The following two occurrences can be indicated:

- $T \leq T_{CRIT}$: The null hypothesis H_0 is accepted. It means that the differences vector co-ordinate values are not significant.
- $T \geq T_{CRIT}$: The null hypothesis H_0 is refused. It means that the differences vector co-ordinate values are statistically significant. In this case we can say that deformation with the confidence level α is occurred.

Analytical process of testing

Definition of the null hypothesis H_0 is the first step according to the equation

$$H_0 = E(s_0^{2^1}) = E(s_0^{2^2}) = \sigma_0^2 , \tag{11}$$

where σ_0 is the selected variation.

F distribution is used at the testing. F distribution has the degrees of freedom f_1 and f_2. Full testing is proceeding in three phases. The first phase is a comparison testing which tests whether the measuring values in epochs are equivalent. In the second phase a global test is realized which would indicate whether statistically meaningful data have occurred in the processed vector. The third phase is an identity test. This test is realized only in a case where the null hypothesis has not been confirmed during global test. The identity test will check the statistic significance of each point individually.

It is suitable to check first of all reference points during testing. If some of the reference point has not passed the test, it means that this point has been moved with a certainty α. Such point should change over to object points or it should be eliminated from the next processing.

If there is a certainty that the reference points are fixed, then only the object points are subject to testing. By a comparison test the test statistics T is applied according to the following equation

$$T = \frac{s_0^{2^I}}{s_0^{2^{II}}} \approx F(f_1, f_2) \,. \tag{12}$$

where I, II are the measuring epochs.

It is searched for a critical value T_{KRIT} in tables of F distribution according to degrees of freedom $f_1 = f_2 = n-k$ or $f_1 = f_2 = n-k+d$.

The test statistics T is compared with the critical value T_{CRIT} and the null hypothesis H_0:

- $T \leq T_{CRIT}$: the null hypothesis H_0 is accepted and it means that measuring values in epochs are themselves equivalent.
- $T \geq T_{CRIT}$: the null hypothesis H_0 is refused and it means that measuring values in epochs are themselves not equivalent.

By global test the test statistics T_G is applied according to the following equation

$$T_G = \frac{\delta\hat{\boldsymbol{C}}^T . \boldsymbol{Q}_{\delta\hat{C}}^{\,1} . \delta\hat{\boldsymbol{C}}^T}{k . s_0^2} \approx F(f_1, f_2) \,, \tag{13}$$

where

$$s_0^2 = \frac{(v^T . \boldsymbol{Q}_L{}^1 v)^1 + (v^T . \boldsymbol{Q}_L{}^1 . v)^2}{f_1 + f_2} \,. \tag{14}$$

The critical value T_{CRIT} is selected from F distribution tables according to the degrees of freedom $f_1 = n$ and $f_2 = n-k$ or $f_1 = 1$ and $f_2 = n-k+d$.

The test statistics T is compared with the critic values T_{CRIT} and the null hypothesis is considered:

- $T \leq T_{CRIT}$: The null hypothesis H_0 is accepted and it means that the co-ordinate differences vector values are minor.
- $T \geq T_{CRIT}$: The null hypothesis H_0 is refused and it means that the co-ordinate differences vector values are meaningful. In this case the third phase should be operated the aim of which would be to find to which points any displacement can be to be allocated.

By identity test the test statistics T_i is applied according to the following equation

$$T_i = \frac{\delta\hat{\mathbf{C}}_i^T . \mathbf{Q}_{\delta\hat{C}}^{-1} . \delta\hat{\mathbf{C}}_i}{s_0^2} \approx F(f_1, f_2) \,. \tag{15}$$

The critical value T_{CRIT} is selected from F distribution tables according to the degrees of freedom $f_1=n$ and $f_2=n-k$ or $f_1=1$ and $f_2=n-k+d$.

The test statistics T is compared with the critic value T_{CRIT} and the null hypothesis H_0 is taken into consideration:

- $T \leq T_{CRIT}$: The null hypothesis H_0 is accepted and it means that the adjusted co-ordinate difference values of tested point are statistically minor.
- $T \geq T_{CRIT}$: The null hypothesis H_0 is refused and it means that the adjusted co-ordinate difference values of tested point are statistically meaningful. This point is moved with expectation α.

After detection of displacement of a point the point is excluded from the following testing and the total file is subject to testing once more.

Determining co-factor matrix of deformation vector

In the same way as the testing of co-ordinate differences could be applied, it is needed to determine the co-factor matrix of co-ordinate differences $\mathbf{Q}_{\delta\hat{C}}$. Its scale is determined by the following equation

$$\mathbf{Q}_{\delta\hat{C}} = \mathbf{Q}_{\hat{C}}^{I} + \mathbf{Q}_{\hat{C}}^{II} - (\mathbf{Q}_{\hat{C}}^{I,II} + \mathbf{Q}_{\hat{C}}^{II,I}) \,. \tag{16}$$

This equation is valid at a simultaneous adjustment of network. At a separate adjustment of deformation network the following equation is valid

$$\mathbf{Q}_{\delta\hat{C}} = \mathbf{Q}_{\hat{C}}^{I} + \mathbf{Q}_{\hat{C}}^{II} \,. \tag{17}$$

It follows from this that it is necessary to choose a respectable structure and follow-up procedures for processing of deformation network.

Graphic analysis method of testing

A graphic form of point displacement is result of this approach and the following equation can be applied

$$\delta\hat{\mathbf{C}}^T . \mathbf{Q}_{\delta\hat{C}}^{-1} . \delta\hat{\mathbf{C}} = T.k.s_0^2 \,. \tag{18}$$

By the above equation an equation of ellipse is presented. It is necessary to know values of semi-axes and swing out angle values of ellipse for the purpose of depicting of the ellipse. The following equation can be used for values of semi-axes $a_{i\alpha}$, $b_{i\alpha}$ of ellipse

$$a_{i\alpha}^2 = ((\mathbf{Q}_{\delta xi} + \mathbf{Q}_{\delta yi}) + \sqrt{(2\mathbf{Q}_{\delta xi} - \mathbf{Q}_{\delta yi})^2 + 4.(\mathbf{Q}_{\delta xi\delta yi}{}^2)}).F(1-\alpha,2,n-k).s_0^2 \,, \tag{19}$$

$$b_{i\alpha}^2 = ((\mathbf{Q}_{\delta xi} + \mathbf{Q}_{\delta yi}) - \sqrt{(\mathbf{Q}_{\delta xi} - \mathbf{Q}_{\delta yi})^2 + 4.(\mathbf{Q}_{\delta xi\delta yi}{}^2)}).F(1-\alpha,2,n-k).s_0^2 \,, \tag{20}$$

where $a_{i\alpha}$ is the major semi-axis of ellipse in mm,
$b_{i\alpha}$ is the minor semi-axis of ellipse in mm.

The swing-out angle φ is determined according to the following equation

$$tg2\varphi_a = \frac{2.\mathbf{Q}_{\delta xi\delta yi}}{\mathbf{Q}_{\delta xi} - \mathbf{Q}_{\delta yi}} \,. \tag{21}$$

These ellipses are called confidence (relative) ellipses. It is possible to form them only if deformation network simultaneous processing procedure is applied. A confidence ellipse is depicted according to design elements with a centre in a point of the second epoch. The positional vector between point positions in the second and in the first epoch is also depicted. The null hypothesis can be defined by a confidence ellipse, which covers the total positional vector in its full extent. The ellipse does not indicate any displacement of considered point if it does no cover the positional vector in its full extent. Then the null hypothesis is refused.

Results of graphic analysis

Measurement and data processing were realized during the spring epochs of years: 1999, 2000, 2001, 2002 and 2003. Time intervals between epochs were twelve months. In this way a positional survey of deformation of the dam Pod Bukovcom was carried-out. It was realized a free unit adjustment of deformation network of object points. This network was processed by means of application of *LSM* approach. A Gauss-Markov's mathematic model was applied for processing procedure. In respect thereof the significance levels and degrees of freedom were determined. The selected network was featured by an adequate redundancy (measurement redundancy).

The position (2D) accuracy of the points of the network Pod Bukovcom was assessed by means of global and local indices.

The global indices

These indices were used for considering of accuracy of network as a whole and they are numerically expressed. If for a network the last numerical value is indicated it means that the observed elements of the network have been most exactly observed and the equalizing adjustment will have also a high degree of accuracy.

The following global indices were considered:

a) *variance global indices*: *tr* ($\boldsymbol{\Sigma}_{\hat{C}}$), i.e. a track (sum) of covariance matrix $\boldsymbol{\Sigma}_{\hat{C}}$,

b) *volume global indices*: *det* ($\boldsymbol{\Sigma}_{\hat{C}}$), i.e. a determinant.

Local indices

In a matter-of-fact-way these indices were point indices by which reliability of network points was featured.

The local indices are mentioned in the following expressions:

a) *mean 2D error:* $\sigma_p = \sqrt{\sigma^2_{\hat{X}_i} + \sigma^2_{\hat{Y}_i}}$,

b) *mean co-ordinate error:* $\sigma_{XY} = \sqrt{\dfrac{\sigma^2_{\hat{X}_i} + \sigma^2_{\hat{Y}_i}}{2}}$,

c) *absolute confidence ellipses:* they were used as a means of considering of real position within range of point accuracy. It is necessary to know constructional elements of ellipses, i.e. major semi-axis a and minor semi-axis b and the bearing φ_a of major semi-axis. It was also necessary to determine the signification α .

The design elements of confidence ellipses were calculated from the cofactor matrix by applying adequate equations. The elements of confidence ellipses are included in *Tab. 1* and the confidence ellipses in *Fig. 3* (Ječný 2001).

Tab. 1: Graphic analysis testing results – elements of confidence ellipses (epoch 2003).

Point	***a*** [mm]	***b*** [mm]	φ_a [^{g}]	**Point**	***a*** [mm]	***b*** [mm]	φ_a [^{g}]
1	10.7	4.6	289.1788	13	6.2	5.1	261.8504
2	11.9	4.5	271.1377	15	6.3	5.4	239.4482
3	7.2	4.3	316.2047	16	6.3	5.3	239.4007
4	7.7	4.4	304.6711	17	6.3	5.3	239.5853
5	18.4	5.1	194.1328	18	6.3	5.3	240.3191
6	11.8	4.5	238.1088	19	6.4	5.2	241.8465
7	12.1	4.5	238.6154	20	6.7	5.1	244.1852
8	6.1	5.4	246.6188	21	8.0	4.7	215.0106
9	5.9	5.5	249.0293	22	8.2	4.7	213.8748
10	5.8	5.5	253.5228	23	8.4	4.6	212.3949
11	5.9	5.3	257.2947	25	13.1	4.3	199.6478
12	6.1	5.2	260.2185	26	19.2	4.2	197.5029

The analytic approach was applied for comparison after processing of results. According to this analysis the global test value T_G corresponded to 1.5498 and the value T_{CRIT} corresponded to 1.8284. From this followed that neither value of the object point indicates any statistically meaningful displacement during period between two measuring epochs. For comparison: The position co-ordinates of points in epoch 2003 were determined with the average mean error of 5.7 mm and in epoch 2002 of 3.2 mm.

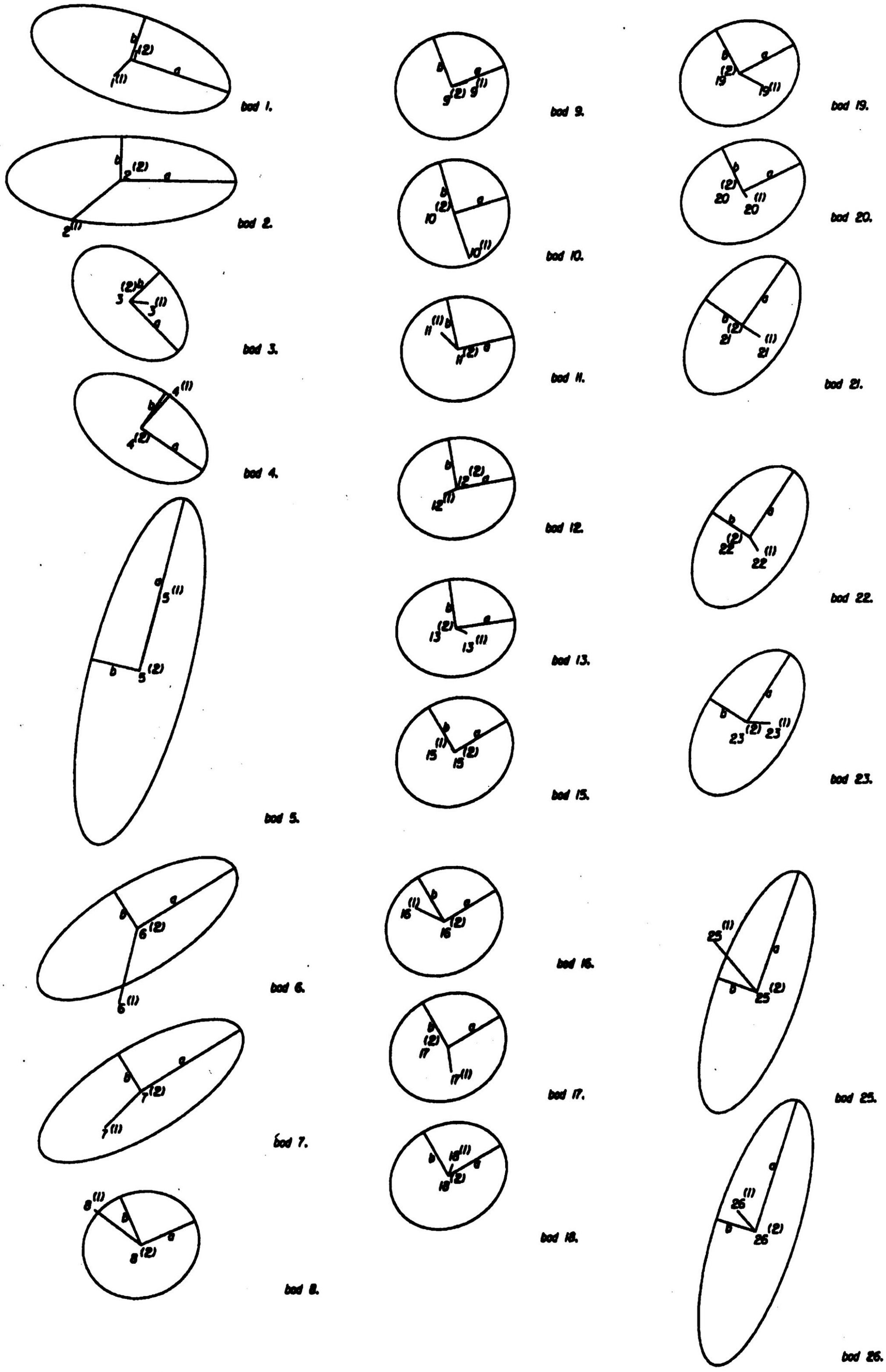

Fig.3: Confidence ellipses (1:1 scale); deformation vectors 1999-2003.

Conclusions

The independent results both of analytical and graphic analysis procedures confirmed the assumption that the object points and thus also the dam object did not note indicate any statistically meaningful displacement with a certainty of 95 %. The confidence ellipses of the points N^{o} 6, N^{o} 8 and N^{o} 25 did not verify the null hypothesis, because the deformation vector did not exceed any ellipse. Sharpness of positional vector was truly insignificant from which the conclusion was deducted that no displacement in these points had occurred.

The bulk dam of waterwork Pod Bukovcom has been observed since finishing of its construction until now. The observations were periodical. The time period between epochs was gradually prolonged from a half-year up to two years after a fixed course of dam object movements. By the results the fixed trend was confirmed. The knowledge results obtained from geodetic analyses processed after each observation are applied for designing and for observation of deformations of similar waterworks. Thereby the assurance of population living in vicinity of the bulk dam can be increased and in this way the eventual economic and ecological damages caused by any emergency of waterwork can be forestalled.

Acknowledgements

The paper resulted from the research project N° 1/0368/03 elaborated by the Department of Geographical Information Systems of Faculty of Mining, Ecology, Process Control & Geotechnologies of Technical University of Košice, Slovak Republic.

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Resumé

Článok prezentuje niektoré výsledky geodetických terestrických polohových meraní v rámci deformačného šetrenia na sypanej hrádzi vodného diela Pod Bukovcom neďaleko Košíc na východnom Slovensku. Vodné dielo, vybudované v 50 až 60-tych rokoch minulého storočia, slúži v prípade havárie ako zásobáreň priemyselnej vody pre US Steel a.s. Košice (predtým VSŽ). Na monitorovacej stanici, pozostávajúcej z 24 objektových bodov stabilizovaných na telese sypanej hrádze a 6 referenčných bodov v netangentnom území okolia telesa hrádze, vykonávajú pracovníci Ústavu geodézie a geografických informačných systémov (ÚGaGIS) Fakulty baníctva, ekológie, riadenia a geotechnológií (F BERG) Technickej univerzity (TU) v Košiciach v rámci svojich výskumných projektov každoročné periodické terestrické polohové a výškové merania od roku 1999 s cieľom posúdiť stabilitu či pohyb hrádze vodného diela. Tieto terestrické merania sú nezávislé od dlhodobých (vyše 40-ročných) periodických meraní realizovaných geodetickými referátmi materských firiem VSŽ a US Steel Košice. Od roku 2001 ÚGaGIS F BERG TU v Košiciach realizuje i družicové navigačné meranie (GPS), pričom výsledky týchto meraní slúžia len k overovacím meraniam smerujúcim k posúdeniu vhodnosti aplikácie GPS do najmä 2D deformačných šetrení.

Realizované terestrické polohové merania spočívajú v meraní dĺžok medzi referenčnými a objektovými bodmi monitorovacej stanice v rôznych kombináciách s cieľom zabezpečiť viacnásobný výsledok 2D súradníc objektových bodov z rôznych kombinácií pretínania napred dĺžkami. K posúdeniu prípadných výškových pohybov hrádze sa realizuje veľmi presná nivelácia.

Nezávislé výsledky analytických a grafických analýz nepotvrdili žiadny signifikantný pohyb na hrádzi. Pri posudzovaní stability bodov monitorovacej siete sypanej hrádze vodného diela pod Bukovcom boli použité

bežné testovacie štatistiky. Objektové body, a tým aj teleso sypanej hrádze, nedoznali akékoľvek štatisticky významné pohyby s určitosťou na 95 %. Konfidenčné elipsy niektorých objektových bodov (napr. body č. 6, 8 a 25) nespĺňali nulovú hypotézu, pretože deformačný vektor presahoval plochu týchto konfidenčných elíps. I napriek tejto skutočnosti po podrobnejšej analytickej analýze presahovanie konfidenčných elíps deformačnými vektormi je pre druh sypanej hrádze, akým je hrádza vodného diela Pod Bukovcom, zo stavebného hľadiska technického predurčenia tejto hrádze zanedbateľné a z tohto aspektu je akceptovaná dedukcia o stabilite uvedených bodov monitorovacej stanice.

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