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MONITORING STATIC DEFORMATION OF THE BULK DAM IN THE EAST SLOVAKIA

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Abstract: Deformations on buildings and structures due to own weight, water pressure, inner temperature, contraction, atmospheric temperature and earth consolidation occur. Especially, it is necessary to embark on monitoring and analysing of deformation effects and movements of any sizeable dams and water basins and so to prevent of their prospective catastrophic effects into environment. The paper is centred on stability of the bulk (roc-fill) dam of the water basin Pod Bukovcom near Košice in the East Slovak Region. Results and analyses of the geodetic terrestrial and GPS measurements on the rock-fill dam are undergone by to test-statistics, the model of stability or prospective movement of the rock-fill dam with time prediction. The paper outputs are incorporated into GIS and information system of U.S. Steel Košice.

1. INTRODUCTION

Deformations and movements of buildings and construction by effect of own weight, water pressure, inside temperature, retraction, atmospheric temperature and earth consolidation, are occurred. These deformations and movements are necessary to investigate according to the philosophy that “all is in the continual movements”. Especially, it is necessary to go into monitoring and analysing deformations and movements of some sizeable building works of the human. The dams belong to the major building works, where the monitoring of these deformations and movements must be done.

The bulk dam Pod Bukovcom is built on the river Idan between the villages Bukovec and Malá Ida in the East Slovakia (Figure 1a). The bulk fagot dam is situated in the morphologically most advantageous profile, in the place of the old approximately 7 m high fagot dam, which was liquidated following the building-up of the up-to-date bulk fagot dam. The industrial water supply for cooling the metallurgical furnace equipments in the company US Steel Košice in a case of damages is the purpose of the dam. The water basin is also for flattening the flow waters and for recreational purposes during the summer time.

2. THE NETWORK OF THE BULK DAM POD BUKOVCOM

Six reference points stabilized outside of the dam bulk fagot dam. The reference points are situated about 50-100 m from the dam (Technické podklady…, 1965-98). The reference points have the labelling from A1 up to F1. These points supplied the old reference points from who's the measurement are performed since 1985. The stabilization of these reference points is realised by the breasting pillars with a thread for the exact forced centring of the surveying equipment (total stations and GPS).

The object points on the bulk fagot dam are set so as they represented the fagot dam geometry and the assumed pressures of the water level on the fagot dam at the best. The points are set in six profiles on the fagot dam. So as the object points transmit of the fagot dam deformations, they had to be approximately stabilized deep 1.8 m. Generally 26 object points are set on the fagot dam (Figure 1b). Two of them are destroyed.

Figure 1a - The bulk dam Pod Bukovcom

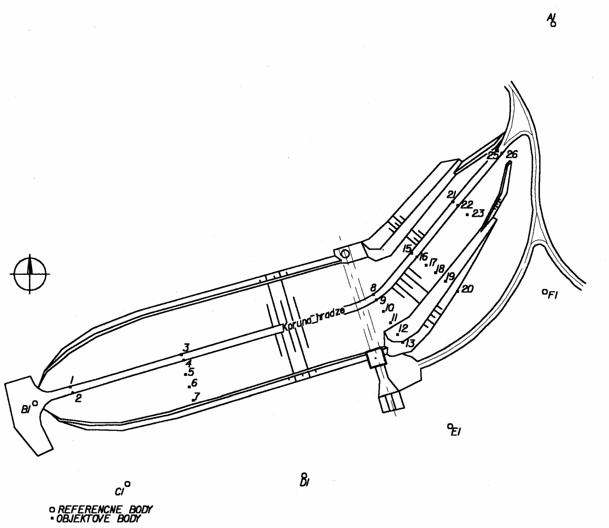

Figure 1b - The network point field of the bulk dam

∘ reference points • object points

3. THE DEFORMITY DETECTION ALGORITHM

Deformity detections are performed according to the concrete procedure technique. This procedure is called the algorithm (Figure2). From the scheme in Figure1b results, that full procedure since the project trough the measurement ends by the obtained adjustment results analyse. The processed results are analysed from the aspect of geometrical or physical properties of the examined object.

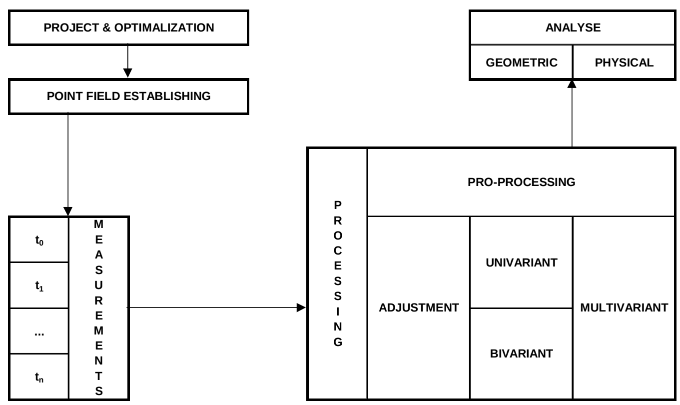

Figure 2 - Scheme of deformity detection algorithm

3.1. The deformity detection analyse

Analyse of the deformation network processed data can be done by the analytic or the analytic-graphic ways. It depends on the used middles for the network congruence. The used methods are varied asunder by the result shape of the results presentation. However, from the point view of the deduction analyse the results presentation are equivalent. From the point of view of the congruence testing analyse is divided into the statistical and deterministic analyses.

The congruence method of the geodetic networks follows out from the base of examination and analyse of the positional co-ordinates from the individual epochs. From the point of view of the tested values the deformity detection analyse methods are divided into the parametric and nonparametric methods.

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

The statistic testing practices are the most frequently used for a purpose of the deformation networks congruence testing? Arbitration whether the network co-ordinate or invariance differences are statistically meaningful or not meaningful is the task of the testing. For this purpose it is necessary to form the null-hypothesis, which has the shape (Ječný 2000, Sedlák 1996, Sedlák and Ječný 2004)

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

or in the shape respectively

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

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

It means that the middle values of the vector of the adjusted co-ordinates or measurements from the first epoch are equalled to the middle value of the vector of the adjusted co-ordinates or measurements from the second epoch.

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

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

The often register for the adjusted co-ordinates of the object points is in the adnichiled form

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

For the null-hypothesis H_0 the equation is also used in the shape

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

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

The test statistics T is compared with the null-hypothesis. The universal test statistics is the most frequently composed on the tested value and middle 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 composed for the co-ordinate differences vector. According to it the test statistics T will be in the shape

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

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

The quadratic form of the co-ordinate divergences is in the numerator and the empirical variation factor s_0 is in the denominator. The test statistics shape after arrangement is

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

where $1\text{-}\alpha$ is the reliability coefficient, α is the confidence level (95% or 99%), f_1, f_2 are the stages of freedom of F distribution (Fischer's distribution) of the accidental variable T, k is the co-ordinates number accessioning into the network adjustment.

The stages of freedom are selected according to the adjustment type. For the free adjustment, they are the equations are valid

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

and for the bonding adjustment

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

where n is number of the measured values entering into the network adjustment, d is the network defect at the network free adjustment.

The test statistics T should be subjugated to a comparison with the critical test statistics T_{CRIT}. T_{CRIT} is found in the tables of F distribution according the network stages of freedom.

Two occurrences can be appeared:

- $T \le T_{CRIT}$: The null-hypothesis H_0 is accepted. It means that the differences vector co-ordinate values are not significant.
- $T \ge T_{CRIT}$: 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 the deformation with the confidence level α is occurred.

3.2. Analytic 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 stages of freedom f_1 and f_2. Full testing is in progress in three phases. The first phase, it is the comparison testing, which tests whether the measurements in the epochs were equivalent. The second phase, it is the realisation of the global test, which will show whether the statistically meaningful data are occurred in the processed vector. The third phase, it is the identification test. This test is realised only in a case when the null-hypothesis is not confirmed at the global test. The identification test will check the statistic significance of each point individually.

To check the reference points at first is suitable at the testing. If some of the reference points do not pass over the test, it will mean that the point is moved with the certainty α. Such point will be changed up among the object points or it will be eliminated from the next processing.

If we have a safety that the reference points are fixed then the object points are only submitted to the testing. The comparison test operates with the test statistics T according to the equation

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

where I,II are the measurement epochs

The critical value T_{KRIT} is searched in the F distribution tables according to the 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 critic value T_{CRIT} and the null-hypothesis H_0 is considered:

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

The global test operates with the test statistics T_G according to the equation

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

where

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

The critic value T_{KRIT} is found in F distribution tables according to the degrees of freedom $f_1=k$, $f_2=n-k$ or $f_1= k+d$, $f_2=n-k+d$.

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 petit.
- $T \geq T_{CRIT}$: 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 must be operated at which to be found which points allocate any displacement.

The identity test operates with the test statistics T_i 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 critic value T_{CRIT} is chosen in the F distribution tables according to the degrees of freedom $f_1=n$ a $f_2=n-k$ or $f_1=1$ a $f_2=n-k+d$.

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

After detection of the point displacement this point is excluded from the following testing and whole file is submitted to testing once more.

3.3. Determining the co-factor matrix of the deformation vector

So as the testing the co-ordinate differences could be operated, it is needed to determine the co-factor matrix of the co-ordinate differences $\boldsymbol{Q}_{\delta\hat{C}}$. Its scale will determine by the following equation

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

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

$$\boldsymbol{Q}_{\delta\hat{C}} = \boldsymbol{Q}^{I}_{\hat{C}} + \boldsymbol{Q}^{II}_{\hat{C}}. \quad (17)$$

From this follows that it is necessary to choose a respectable structure and a follow-up procedures in the deformation network processing.

3.4. Analytic and graphic way of testing

The graphic shape of point displacement is a result and we can used the following equation

$$\delta\hat{\boldsymbol{C}}^{T}.\boldsymbol{Q}^{1}_{\delta\hat{C}}.\delta\hat{\boldsymbol{C}} = T.k.s_0^2. \quad (18)$$

This equation presents the ellipse equation. The ellipse half-axle values and the ellipse swing out angle values round a co-ordinate system are necessary to know for a purpose of the ellipse depict. The following equation can be used for the ellipse half-axle values $a_{i\alpha}, b_{i\alpha}$

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

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

where $a_{i\alpha}$ is the ellipse main half-axle in mm,

$b_{i\alpha}$ is the ellipse adjacent half-axle in mm.

The swing out angle of φ is determined according to the equation

$$tg2\varphi_a = \frac{2.\boldsymbol{Q}_{\delta xi\delta yi}}{\boldsymbol{Q}_{\delta xi} - \boldsymbol{Q}_{\delta yi}}. \quad (21)$$

These ellipses are named the confidence (relative) ellipses. It is possible to form them only in a case if the deformation network simultaneous processing procedure is appointed. The confidence ellipse is depicted according to the design elements with a centre in the point from the second epoch. The positional vector between the point position from the second and the first epoch is also depicted. The null-hypothesis is definable by the confidence ellipse, which covers whole positional vector in a full scale. The ellipse does not characterise a displacement of the considered point if it covers the positional vector in a full scale. The null-hypothesis is accepted. The ellipse characterises the displacement of the considered point if it does not cover the positional vector in a full scale. The null-hypothesis is refused.

3.5. Results of the analytic-graphic analyse

Measurement and data processing were realized in the epochs: spring 1999, 2000, 2001, 2002 and 2003. Twelve months were the time period between the epochs. The positional survey of deformation of the dam Pod Bukovcom was carried out. A free unit adjustment of the deformation network of the object points was realized. The network was processed by means of using LSM. Gauss-Markov mathematic model was applied into the processing procedure. In respect thereof the significance levels and the degrees of freedom were determined. The selected network was an adequate redundancy (measurements redundancy).

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

Global indices were used for an accuracy consideration of whole network, and they are numerically expressed. The network, which indicates have the last number, means that its observed elements were the most exactly observed, and the equal adjustment has also a high accuracy degree.

The following global indices were considered:

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

Local indices were as the matter of fact the point indices, which characterize the reliability of the network points.

The local indices were in the following expressions:

- *the middle 2D error:* $\sigma_p = \sqrt{\sigma_{\hat{X}_i}^2 + \sigma_{\hat{Y}_i}^2}$,
- *the middle co-ordinate error:* $\sigma_{XY} = \sqrt{\dfrac{\sigma_{\hat{X}_i}^2 + \sigma_{\hat{Y}_i}^2}{2}}$,
- *the confidence absolute ellipses* which were served for a consideration of the real position in the point accuracy. We need know the ellipsis constructional elements, i.e. the semi-major axis a, the semi-minor axis b and the bearing φ_a of the semi-major axis. We had to also determine the signification α.

The confidence ellipses design elements were calculated from the cofactor matrix with using adequate equations. The confidence ellipses design elements are included in Table 1 and the confidence ellipses in Figure 3 (Ječný 2000, Sedlák and Ječný 2004).

The analytic analyse was implemented for a comparison after the results processing. According to this analyse the global test value T_G responded to 1.5498 and the value T_{CRIT} responded to 1.8284. From this follows that neither objects point did not note down statistically meaningful displacement during a period between the measurement epochs.

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

Table 1 - The analytic-graphic testing results –the confidence ellipses elements (2003)

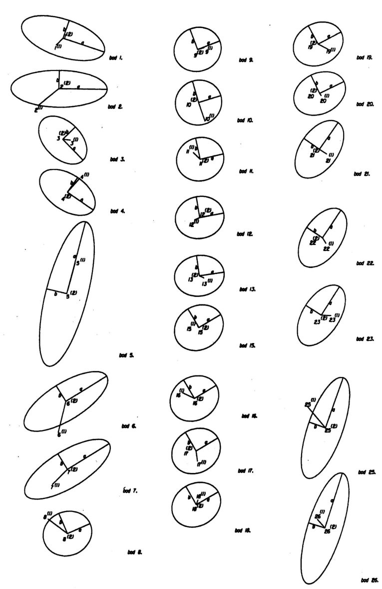

Figure 3 - The confidence ellipses; the deformation vectors: 1999-2003

4. CONCLUSIONS

The independent results from the analytic and analytic-graphic analyses confirmed an assumption that the object points and thereby also the dam object did not note down any statistically meaningful displacement with the definiteness on 95 %. The confidence ellipses of the points No: 6, 8 and 25 do not verify the null-hypothesis because the deformation vector does not exceed of an ellipse. Shrillness of the positional vector is indeed insignificant from which a conclusion was deducted that the displacement at these points was not occurred.

The observation of the bulk dam of the water work Pod Bukovcom is performed since its construction finishing as yet. The observations are periodical. A time period between epochs is gradually elongated since a half of year till two years time after a fixed course of the dam object movements. The results just confirmed this fixed trend. From geodetic analyses processed after each observation the obtained knowledge are applied at a designing and observation of similar water works deformations. Thereby an assurance is increased for population living nearby of the dam and also thereby economic and ecological damages caused by any emergency on the water work can be forestalled.

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