TEST ANALYSES OF DAM DEFORMATIONS FOR SECURITY OF PEOPLE AND ENVIRONMENTAL PROTECTION

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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 analyzing of deformation effects and movements of any sizeable dams and water basins and so to prevent of their prospective catastrophic effects in the environment and also human lives. The paper is centered on the stability of the earthen dam of the Pod Bukovcom near town Košice in the East Slovak Region. Results and analyses of the geodetic terrestrial and GPS measurements on the earthen dam are undergone by to test-statistics, the model of stability or prospective movement of the earthen dam with time prediction. The paper outputs are incorporated into GIS and information system of U.S. Steel Košice.

Keywords: Deformation, dam, analyse, security

Introduction

Deformations and movements of buildings and construction by effect of own weight, water pressure, inside temperature, retraction, atmospheric temperature and earth consolidation are occurring. 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 analyzing 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. Some dams have also strategic signification and many of them must be protected by reason of economic and policy and military and criminality prevention strategy (Kazanský 2011, Kříha 2011, Nečas 2009, Pána 2012, Sedlák 1996, 2012, Svatoš 2012).

The earthen dam Pod Bukovcom is built on the river Idan between villages Bukovec and Malá Ida in the Eastern Slovakia (Fig.1). The earthen dam is situated in the morphologically most advantageous profile, in the place of the old approximately 7 m high and 220 m long dam body, which was liquidated following the building-up of the up-to-date earthen dam. The industrial water supply for cooling the metallurgical furnace equipment in the company U.S. Steel Košice in a case of damages is the purpose of the dam. The water basin is also for flattening the flowing waters and for recreational purposes during the summer time.

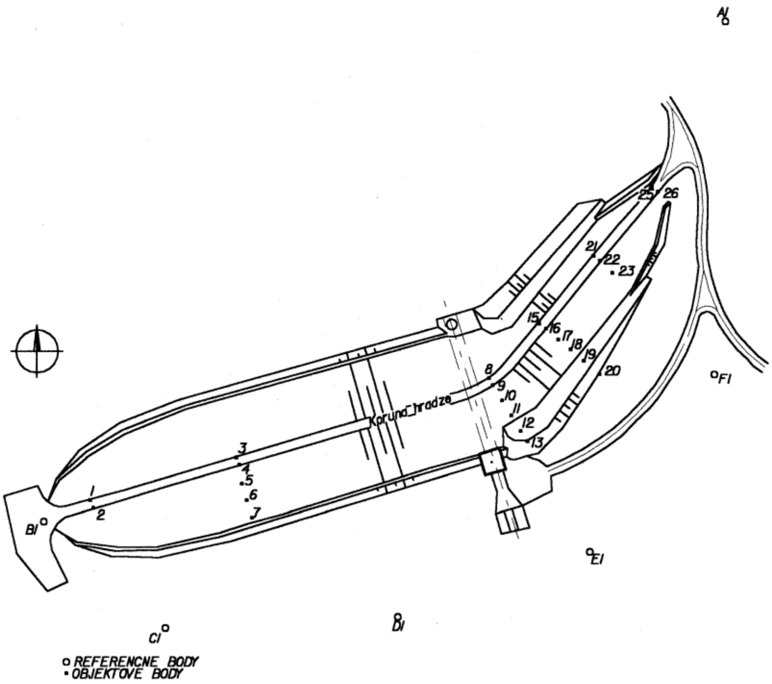
Fig.1: The earthen dam Pod Bukovcom.

The network of the earthen dam

Six reference points stabilized outside of the earthen dam. The reference points are situated about 50-100 m from the dam. 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 realized by the breasting pillars with a thread for the exact forced centering of the surveying equipment (total stations and GPS).

The object points on the earthen dam are set so as they represented the earthen dam geometry and the assumed pressures of the water level on the earthen dam at the best. The points are set in six profiles on the earthen dam. So as the object points transmit of the earthen dam deformations, they had to be approximately stabilized deep 1.8 m. Generally 26 object points are set on the earthen dam (Fig.2). Two of them are destroyed

Fig.2: The network point field of the earthen dam (○ reference points, ● object points).



The deformity detection algorithm

Deformation detections are performed according to the concrete procedure technique. This procedure is called the algorithm (Fig.3). From the scheme in Fig.3 it has resulted that full procedure since the project through the measurement ends by the obtained adjustment results analysis. The processed results are analyzed from the aspect of geometrical or physical properties of the examined object (Sedlák 1996, 2012, Staňková & Černota 2010).

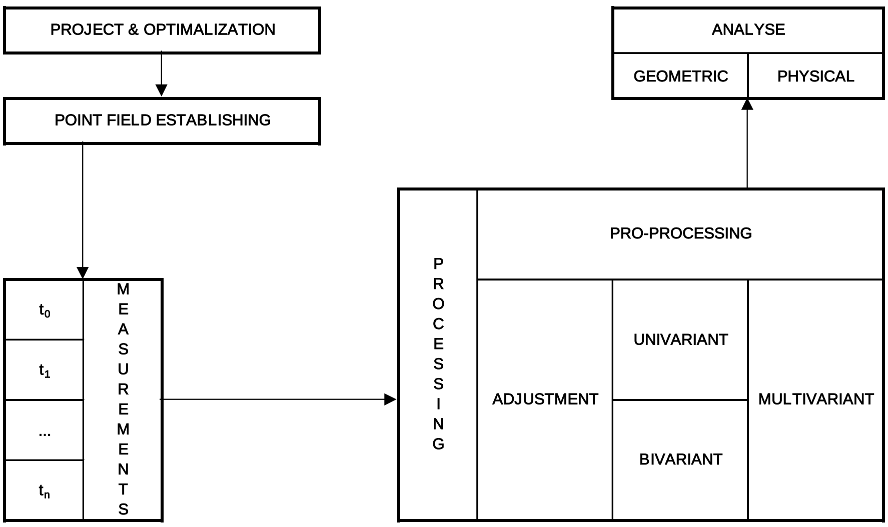


Fig.3: Scheme of deformation detection algorithm.

The deformation 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 methods used are varied asunder by the resulting 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 analysis is divided into the statistical and deterministic analyses.

The congruence method of the geodetic networks follows out from the base of examination and analysis of the positional coordinates from the individual epochs. From the point of view of the tested values the deformity detection analysis methods are divided into the parametric and nonparametric methods. The parametric testing methods make use of the coordinate 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 estimating model LSM (Last Square Method) or by means of the robust statistic models (Jecny & Sedlak 2004, Sedlak 1996, 2012).

The statistic testing practices are the most frequently used for a purpose of the deformation network congruence testing? Arbitration whether the network coordinates 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

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

or in the shape respectively

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

where $\hat{\boldsymbol{C}}^i$ is the vector of the adjusted coordinates 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 coordinate differences $\delta\hat{\boldsymbol{C}}^i$ is valid the equation

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

The often register for the adjusted coordinates of the object points is in the annulled form

$$\hat{\boldsymbol{C}}^1 - \hat{\boldsymbol{C}}^2 = 0. \qquad (4)$$

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 are the most frequently composed of 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

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

where n is the 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:

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

Analytic process of testing

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

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

where is the selected variable.

F distribution is used in 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 realization of the global test, which will show whether the statistical meaningful data are occurring in the processed vector. The third phase, it is the identification test. This test is realized only in a case when the null-hypothesis are 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 process.

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

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

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 critical 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 critical 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's values T_{CRIT} and the null-hypothesis are considered:

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

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

Determining the co-factor matrix of the deformation vector

So as the testing the coordinate differences could be operated, it is needed to determine the co-factor matrix of the coordinate differences $\boldsymbol{Q}_{\delta\hat{C}}$. Its scale will determine by the following equation (Sedlák 2012)

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

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

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

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

Analytic and graphic way of testing

The graphic shape of point displacement is a result and we can use the following equation (Ječný & Sedlák 2004, Sedlák 2012)

$$\delta\hat{\boldsymbol{C}}^{T}.\boldsymbol{Q}_{\delta\hat{C}}^{1}.\delta\hat{\boldsymbol{C}} = T.k.s_{0}^{2}. \qquad (18)$$

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 $a_{i\alpha}, b_{i\alpha}$

$$a_{i\alpha}^{2} = ((\boldsymbol{Q}_{\delta xi} + \boldsymbol{Q}_{\delta yi}) + \sqrt{(2\boldsymbol{Q}_{\delta xi} - \boldsymbol{Q}_{\delta yi})^{2} + 4.(\boldsymbol{Q}_{\delta xi\delta yi}{}^{2})}).F(1-\alpha,2,n-k).s_{0}^{2}, \qquad (19)$$

$$b_{i\alpha}^{2} = ((\boldsymbol{Q}_{\delta xi} + \boldsymbol{Q}_{\delta yi}) - \sqrt{(\boldsymbol{Q}_{\delta xi} - \boldsymbol{Q}_{\delta yi})^{2} + 4.(\boldsymbol{Q}_{\delta xi\delta yi}{}^{2})}).F(1-\alpha,2,n-k).s_{0}^{2}, \qquad (20)$$

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

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

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

$$tg2\varphi_{a} = \frac{2.\boldsymbol{Q}_{\delta xi\delta yi}}{\boldsymbol{Q}_{\delta xi} - \boldsymbol{Q}_{\delta yi}}. \qquad (21)$$

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 center 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 characterize a displacement of the considered point if it covers the positional vector in a full scale. The null-hypothesis is accepted. The ellipse characterizes the displacement of the considered point if it does not cover the positional vector in a full scale. The null-hypothesis are refused.

Results of the analytic and graphic analyse

GPS measurements and data processing were realized in the epochs (always in spring) since 1999 till 2012. Twelve months were the time period between the epochs. The positional survey of deformation of the earthen 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 (measurement redundancy).

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

The global indices were used for an accuracy consideration of the 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.

The 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: $\sigma_p = \sqrt{\sigma^2_{\hat{X}_i} + \sigma^2_{\hat{Y}_i}}$,
- the middle co-ordinate error: $\sigma_{XY} = \sqrt{\dfrac{\sigma^2_{\hat{X}_i} + \sigma^2_{\hat{Y}_i}}{2}}$,
- the confidence absolute ellipses which were served for a consideration of the real position in the point accuracy. We need to 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 .

Tab.1: The analytic-graphic testing results – the confidence ellipses elements (2012).

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

The confidence ellipses design elements were calculated from the cofactor matrix by using adequate equations. The confidence ellipses design elements are included in Tab.1 (Sedlák 2012).

The analytic analysis was implemented for a comparison after the results processing. According to this analysis 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.

Conclusion

The independent results from the analytic and analytic-graphic analyses confirmed an assumption that the object points and thereby also the earthen 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 earthen dam Pod Bukovcom has been 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 earthen dam object movements. The results just confirmed this fixed trend. From geodetic analyses processed after each observation the obtained knowledge is applied at a designing and observation of similar water works deformations (STN 73 0405). Thereby an assurance is increased for population living nearby of the earthen dam and also thereby economic and ecological damages caused by any emergency on the water work can be forestalled.

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