DEFORMATION ANALYSIS AT THE MAIN DAM FROM THE STEJĂRIŞ COMPLEX, OCNA MUREŞ

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***Abstract**: The main goal in the geodetic activity of land and building monitoring is to determine any displacement or deformation, to ensure the stability and also to protect the environment. The analysis of the repeated geodetic observations gives the oportunity to form statistical statements concerning real displacements and deformations evolution. The main stages of displacement and deformation analysis using Pelzer method are: geodetic observation adjustment for different measurement epochs, applying congruency global tests in order to check if there are any significant displacements, and, if there are, their localisation. As a case study, we chose the Main Dam from the Stejăriş Complex, Ocna Mureş.*

***Keywords**: deformation analysis, significant displacement, congruency global test, localisation*

1. Introduction

The main goal in repeated geodetic observations for displacement and deformation analysis is to show the character of the changes of yhe building ocurred between the measurement epochs, to highlight the displacement and deformation fenomena or the stability of the building.

In order to achieve this, the monitoring geodetic network should contain both object points, placed on observed objective and moving along with it, and fererence points, placed in stable ground, outside the influence area of the observed objective – Fig. 1.

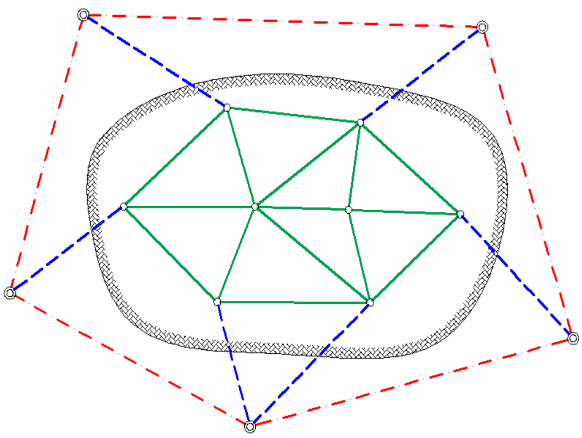

Fig. 1. Monitoring geodetic network – general case

2. The functional – stochastic model

The position of a point will result from the processing of geodetic observations al different measurement epochs. For geodetic observations adjustment, it is used the functional model, defined by the relation - [5]:

$$\begin{bmatrix} v_1 \\ v_2 \\ ... \\ v_k \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & ... & A_{1k} \\ A_{21} & A_{22} & ... & A_{2k} \\ ... & ... & & ... \\ A_{k1} & A_{k2} & ... & A_{kk} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ ... \\ x_k \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \\ ... \\ l_k \end{bmatrix}$$

and the stochastic model, defined by the relation - [5]:

$$C_{mm} = \sigma_0^2 Q_{mm} = \sigma_0^2 \begin{bmatrix} Q_{11} & 0 & ... & 0 \\ 0 & Q_{22} & ... & 0 \\ ... & ... & & ... \\ 0 & 0 & ... & Q_{kk} \end{bmatrix}$$

In statistical terms, there is the basis hypothesis, H_B:

$$H_B: \quad M\left(s_{01}^2\right) = M\left(s_{02}^2\right) = ... = M\left(s_{0k}^2\right) = s_0^2$$

where M is the average (mathematical expectation).

3. The congruency global test

There are considered two measurement epochs, E1 and E2. The null hypothesis establishes weather there are significant displacements of the monitoring geodetic network points between the two measurement epochs considered – [5]:

$$H_0: \quad M(x_1) = M(x_2),$$

by assuming that, for the two measurement epochs, the coordinate differences are very small and may be attributed to measurement errors.

We introduce the coordinate differences vector, d:

$$d = x_2 - x_1$$

and the corresponding cofactor matrix, Q_d:

$$Q_d = Q_{x_1x_1}^{+} + Q_{x_2x_2}^{+} = \left(A_1^T P_1 A_1\right)^{+} + \left(A_2^T P_2 A_2\right)^{+},$$

It will get the quadratic form:

$$\theta^2 = \frac{d^T Q_d d}{h}$$

which is a first step in the deformation analysis. The quadratic form θ^2 has the same rank h as the matrix Q_d.

We will be able to calculate:

$$F = \frac{\theta^2}{S^2}$$

If $F \le F_{1-\alpha, f_0, f_k}$, then the null hypothesis, H_0, will be accepted: the monitoring geodetic network points didn't suffer any significant displacement between the two measurement epochs. Otherwise, the alternative hypothesis, H_α, will be accepted: between the two measurement epochs, there are monitoring geodetic network points that suffered significant displacements. In this case, there will be the next step, the localisation of the points that suffered significant displacements.

4. The localisation of the points with significant displacements

for the localisation of the points with significant displacements, we use the maximum inconsistencies method.

The complete information concerning the geodetic network congruency between the two measurement epochs is held in the two quadratic forms, θ^2 şi Ω.

When calculating the quadratic form θ^2, we take account of network configurations at the two measurement epochs and the limit value accepted for the point displacements.

The principle of the localisation of points with significant displacements is that each common point of the monitoring geodetic network is considered to have suffered a significant displacement.

In the first phase, the coordinate differences vector and the covariance matrix are divided into two parts – [4]:

$$d = \begin{bmatrix} d_S \\ d_O \end{bmatrix}$$

$$Q_d = P_d = \begin{bmatrix} P_{SS} & P_{SO} \\ P_{OS} & P_{OO} \end{bmatrix}$$

The coordinate differences vector d is divided into two vectors, d_S for points considered to be stable and d_O for points considered to be unstable.

Using the transformation formulas for Gauss method:

$$\bar{d}_S = d_S + P_{SS}^{-1} P_{SO} d_O$$

$$\bar{P}_{SS} = P_{SS} - P_{SO} P_{OO}^{-1} P_{OS} \ ,$$

provides a divisation of R into two sums of variables stochasticaly independent:

$$R = d^T P_d d = d_S^T P_{SS}^{-1} d_S + \left(\bar{d}_S\right)^T P_{OO} \bar{d}_O$$

The significant displacements between the two measurement epochs are determined when applying the congruencz global test. The point with the maximum discrepancy is considered unstable point:

$$\theta^2{}_{\max} = \max\left(\theta_i^2, \quad for \ \ i = \overline{1, p}\right)$$

then we use a new congruencz global test in order to determine if there are some more points with significant displacements and then a new problem of localisation – [1].

Upon completion of the calculations, there will determined the stable points that suffered no significant displacements and also the unstable points, that suffered significant displacements.

5. Case study

As a case study, we have chosen the Main Dam from the Stejăriş Complex, Ocna Mureş. For this objective, we took into account the geodetic observations at two measurement epochs, E1 (2009) and E2 (2010), in order to determine the stability of the dam – Fig. 2.

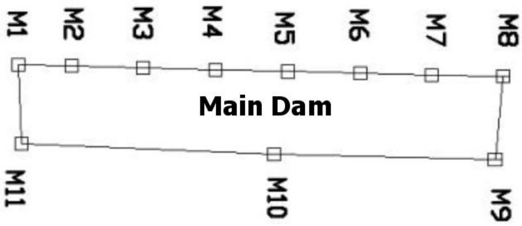

Fig. 2. The monitoring geodetic network for the Main Dam from the Stejăriş Complex, Ocna Mureş

Tab.1. Geodetic observations at the two measurement epochs

No.	From	To	meas. Δ*h* [m]		Dist. [m]
			E1	E2	
1	M11	M1	-0.359	-0.355	55.806
2	M1	M2	1.209	1.210	37.016
3	M2	M10	0.654	0.634	49.292
4	M10	M11	-1.506	-1.489	50.407
5	M3	M2	-2.493	-2.493	50.507
6	M3	M9	-3.697	-3.736	49.916
7	M9	M10	1.859	1.877	49.878
8	M3	M4	-2.602	-2.605	49.928
9	M8	M4	-0.996	-0.995	58.812
10	M8	M9	-2.092	-2.126	153.570
11	M4	M5	0.909	0.933	175.210
12	M5	M6	1.356	1.358	45.161
13	M7	M6	-0.763	-0.740	81.216
14	M7	M8	-2.034	-2.037	52.051

Tab. 2. Measurement adjustment

From	To	E1			E2		
		meas. Δ*h* [m]	v [mm]	adjst. Δ*h* [m]	meas. Δ*h* [m]	v [mm]	adjst. Δ*h* [m]
M11	M1	-0.359	-1.442	-0.360	-0.355	6.002	-0.349
M1	M2	1.209	-1.630	1.207	1.210	0.001	1.210
M2	M10	0.654	-1.431	0.653	0.634	-4.200	0.630
M10	M11	-1.506	2.504	-1.503	-1.489	3.600	-1.485
M3	M2	-2.493	-1.922	-2.495	-2.493	-2.007	-2.495
M3	M9	-3.697	-0.275	-3.697	-3.736	-7.802	-3.744
M9	M10	1.859	-2.077	1.857	1.877	3.401	1.880
M3	M4	-2.602	-1.801	-2.604	-2.605	-7.976	-2.613
M8	M4	-0.996	2.084	-0.994	-0.995	4.118	-0.991
M8	M9	-2.092	2.610	-2.089	-2.126	-6.592	-2.133
M4	M5	0.909	-1.051	0.908	0.933	4.644	0.938
M5	M6	1.356	2.244	1.358	1.358	6.113	1.364
M7	M6	-0.763	3.560	-0.759	-0.74	4.980	-0.735
M7	M8	-2.034	-1.718	-2.036	-2.037	-7.870	-2.045

Tab. 3. Precision estimation

	E1	E2
Ω	0.950	7.083
s_0^2	0.562	1.536

5.1. Testing the homogeneity of the monitoring geodetic network

The null hypothesis is defined by the relation:

$$H_0: \quad M(s_{01}^2) = M(s_{02}^2) = s_0^2$$

For verifying the test, we will calculate the test statistic:

$$F = \frac{s_{01}^2}{s_{02}^2} = \frac{0.562}{1.536} = 0.366$$

From the Fisher-Snedecor Distribution Table, there will be extracted the critical value $F_{1-\alpha, f_1, f_2} = F_{0.95,3,3} = 9.28$. Because $F < F_{1-\alpha, f_1, f_2}$, the null hypothesis is, so the monitoring geodetic network is considered homogenous for the two measurement epochs.

5.2. Congruency global test

The null hypothesis for the network congruency is:

$$H_0: \quad M(x_1) = M(x_2)$$

The coordonate differences vector:

$$d^T = [1 \quad 1 \quad -1 \quad 1 \quad 19 \quad 25 \quad 1 \quad -5 \quad 36 \quad 20 \quad 1]$$

The cofactor coordonate differences matrix:

$$Q_d = \begin{bmatrix} 0.09 & -0.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.03 \\ -0.05 & 0.13 & -0.04 & 0 & 0 & 0 & 0 & 0 & 0 & -0.04 & 0 \\ 0 & -0.04 & 0.12 & -0.04 & 0 & 0 & 0 & 0 & -0.04 & 0 & 0 \\ 0 & 0 & -0.04 & 0.08 & -0.01 & 0 & 0 & -0.03 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.01 & 0.05 & -0.04 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.04 & 0.06 & -0.02 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.02 & 0.06 & -0.03 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.03 & 0 & 0 & -0.03 & 0.08 & -0.01 & 0 & 0 \\ 0 & 0 & -0.04 & 0 & 0 & 0 & 0 & -0.01 & 0.09 & -0.04 & 0 \\ 0 & -0.04 & 0 & 0 & 0 & 0 & 0 & 0 & -0.04 & 0.12 & -0.04 \\ -0.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.04 & 0.07 \end{bmatrix}$$

For verifying the test, we will calculate the test statistic:

$$F = \frac{\theta^2}{S^2} = 11.964$$

From the Fisher-Snedecor Distribution Table, there will be extracted the critical value $F_{1-\alpha,h,f} = F_{0.95,11,6} = 4.03$. Because $F > F_{1-\alpha,h,f}$, the null hypothesis is rejected, so in the geodetic network there are points with significant displacements between the two measurement epochs. The next step is the localisation of the points with significant displacements.

5.3. Localisation of points with significant displacements

Tab. 4. Iteration 1 – for all 11 points of the geodetic network

Pct.	$\bar{d}_S$	θ_i^2	Observations
M1	0.000	0.000	
M2	-0.515	0.008	
M3	-1.371	0.056	
M4	0.201	0.001	
M5	0.067	0.000	
M6	-1.314	0.029	
M7	0.771	0.009	
M8	-0.133	0.000	
M9	2.712	0.171	max => M9 significantly displaced
M10	0.733	0.016	
M11	-0.998	0.018	

For checking if there are some more points with significant displacements, there will be calculated tha test statistic: $F = 123.523$, and from the Fisher-Snedecor Distribution Table there will be extracted the critical value $F_{1-\alpha,h,f} = 4.06$. Because $F > F_{1-\alpha,h,f}$, the null hypothesis is rejected, so in the geodetic network there still are points with significant displacements between the two measurement epochs, resulting the 2nd iteration, for 10 points, after elliminating the point M9.

Tab. 5. Iteration 2 – for 10 points

Pct.	$\bar{d}_S$	θ_i^2	Observations
M1	0.000	0.000	
M2	-0.515	0.008	
M3	-0.166	0.001	
M4	0.201	0.001	
M5	0.067	0.000	
M6	-1.314	0.029	
M7	0.771	0.009	
M8	0.415	0.003	
M10	1.933	0.112	max => M10 significantly displaced
M11	-0.998	0.018	

$$F = 133.149; \qquad F_{1-\alpha,h,f} = 4.10$$

Because $F > F_{1-\alpha,h,f}$, the null hypothesis is rejected, so in the geodetic network there still are points with significant displacements between the two measurement epochs.

Tab. 6. Iteration 3 – for 9 points

Pct.	$\bar{d}_S$	θ_i^2	Observations
M1	0.000	0.000	
M2	0.089	0.000	
M3	-0.166	0.001	
M4	0.201	0.001	
M5	0.067	0.000	
M6	-1.314	0.029	max => M6 significantly displaced
M7	0.771	0.009	
M8	0.415	0.003	
M11	0.052	0.000	

$$F = 97.059; \qquad F_{1-\alpha,h,f} = 4.15$$

Because $F > F_{1-\alpha,h,f}$, the null hypothesis is rejected, so in the geodetic network there still are points with significant displacements between the two measurement epochs.

Tab. 7. Iteration 4 – for 8 points

Pct.	$\bar{d}_S$	θ_i^2	Observations
M1	0.000	0.000	
M2	0.089	0.000	
M3	-0.166	0.001	
M4	0.201	0.001	
M5	-1.920	0.051	max => M5 significantly displaced
M7	-0.204	0.001	
M8	0.415	0.003	
M11	0.052	0.000	

$$F = 14.532; \qquad F_{1-\alpha,h,f} = 4.21$$

Because $F > F_{1-\alpha,h,f}$, the null hypothesis is rejected, so in the geodetic network there still are points with significant displacements between the two measurement epochs.

Tab. 8. Iteration 5 – for 7 points

Pct.	$\bar{d}_S$	θ_i^2	Observations
M1	0.000	0.000	
M2	0.089	0.000	
M3	-0.166	0.001	
M4	-0.052	0.000	
M7	-0.204	0.001	

M8	0.415	0.003	max => M8 significantly displaced
M11	0.052	0.000	

$$F = 2.164; \qquad F_{1-\alpha,h,f} = 4.28$$

Because $F < F_{1-\alpha,h,f}$, the null hypothesis is accepted, so in the geodetic network there are no more points with significant displacements between the two measurement epochs.

Tab.9. Deformation analysis results

Stable points:	M1	M2	M3	M4	-	-	M7	-	-	-	M11
Unstable points:	-	-	-	-	M5	M6	-	M8	M9	M10	-
d	1	1	-1	1	-19	-25	1	5	36	20	1
$\bar{d}_S$	0.000	0.089	-0.166	-0.052	-1.920	-1.314	-0.204	0.415	2.712	1.933	0.052

6. Conclusions

Geodetic observations processing in order to determine displacements and deformations presents a high level of complexity and a huge volume of computations. All these are necessary to be done using statistical methods, this way we will not determine simple coordinate differences, but also analize their statistical significance.

The displacements determined for the observed objective are pretty normal considering the alternating seasons and the high level of underground water, so there is no need to take preventive measures, but the monitoring is still needed.

7. References

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