STATISTICAL ANALYSIS AND DISPLACEMENT DETERMINATION USING DIFFERENT GPS SESSIONS. AN APPLICATION ON DAM OF THESARUS.

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ABSTRACT

In the present study an effective data analysis for monitoring large structures using different GPS sessions is presented. A high accuracy GPS network, consisting of six (6) reference points and twenty-six (26) control points was measured on Dam of Thesaurus which is on of the biggest Dam in Europe and belongs to the public power corporation. The GPS data were collected during two independent campaigns on October 2003 and 2005, using six dual frequency GPS receivers. The baseline defined by the six (6) points, ranged from 200 to 800 meters in length. The deformation process followed two steps. In the first step adjustments for each GPS campaign were applied, in order to test their quality. In the second step simultaneous adjustment using all measurement epochs with displacement estimation was performed. In each step of the above schemes a statistical assessment was also analyzed and performed in order to test the significance of the estimated parameters. Finally, an interpretation of the results at this interesting structure was attempted.

1. INTRODUCTION

The purpose of a deformation survey is to determine whether the monitored object is deformed or not. In various countries, authorities require that dams and reservoirs larger than a certain magnitude must be systematically monitored by geodetic and geophysical techniques to ensure their structural integrity and the safety of the public. In this paper a monitoring scheme using results from GPS data process is presented.

2. DESCRIPTION OF THESARUS DAM

Thesarus Dam is located in northern Greece about of 200 km northeast from the city of Thessaloniki. The dam was constructed during 1983 – 1995 and it belongs to the public power corporation for electricity generation. Thesarus dam is constructed by earthen material with argillaceous central core. It is one of the biggest dams in Europe with maximum structural height 175 m and a crest length of 400 m. The dam casts in a total of five sections with upper-water elevation at 390 m. The surface area of its reservoir is equal to 18 Km^2 and the water elevation is at 320-380 m. Figure 1 shows a view of the dam's main structure and also a big part of the reservoir. Usually, these structural kinds of dams show displacements at the order of a few cm instead of the concrete dams whose values are about one order of magnitude lower.

Figure 1: The Thesarus Dam and its reservoir

3. MONITORING NETWORK AND GPS DATA PROCESS

For monitoring dam structural behavior a geodetic network consisting of six (6) reference points and twenty-six (26) control points was established by the power public corporation. Some of the reference stations are established close to abutments and some others in the neighborhood area but not over 800 m away from the dam. The reference points were concrete cylinder pillars with 1 meter height and 0.4m diameter (see figure 2). All of the control points, which consist of small concrete pillars, are on the crest and the downstream face of the dam (see figure 3). Two GPS campaigns were took place in 2003 and 2005. The GPS data was collected in two days for both campaigns using eight dual frequency receivers from Leica (system 300 and 500) and Thales (Z-Max). All equipments used in both campaigns belong to department of geodesy and surveying. The baselines length that defined by the six reference points, ranged from 200 to 800 meters. In order to get precise ITRF coordinates for all gps benchmarks, one of the reference points was first determined from the Euref station AUT1 using all the recording data within the campaign. At least two points were kept common in any successive pair of sessions. Recording time varies from 45 min to three hours of continuous data with 15-sec. observation rate and 15°cut-off angle. The scope of these points is to link sites (from different sessions) which were not measured simultaneously. Data was processed using Leica ski-pro software, using precise ephemerides and Hopfield's model to account for the tropospheric refraction. In order to avoid the effect of mixing different antennas, all the phase offsets and variations were properly imported in the processing software. A total number of 168 baselines for the first campaign and 142 for the second were performed. The final solution was derived directly from L1 and L2 ambiguity resolution (introducing local ionospheric models) in order to avoid the noise amplification using the L3 linear combination [3],[7],[8]. All the unknown ambiguities numbers are fixed correctly to their integer values using the FARA strategy [5].

Figure 2: Reference point with Thales Z-MAX GPS

Figure 3: Control point with Leica GPS system 500

4. DATA ANALYSIS

Monitoring large deformable structures has become necessary from various reasons. These reasons may be geophysical (micro-seismic activity), geological, or changes of structure forces usually due to a difference of the water elevation at the dam reservoir. The monitoring technique which applies to this kind of networks is the simultaneous adjustment of all the observing epochs using the well known adjustment algorithm, or using the specific partitioned algorithm which will be described below.

As we have already mentioned, in the case of the adjustment of geodetic networks for monitoring large deformable structures there are:

- Observations which took place in different epochs,
- Points which change their position from epoch to epoch and
- Points which remain "stable" for all the observing epochs.

The system of observing equations for the measurements which took place in m epochs, is written as [10]

$$\mathbf{b} = \dot{\mathbf{A}}\,\dot{\mathbf{x}} + \ddot{\mathbf{A}}\,\ddot{\mathbf{x}} + \mathbf{D}\,\mathbf{y} + \mathbf{v} \tag{1}$$

where $\dot{\mathbf{x}}$ is the approximate coordinate correction vector of reference points, $\ddot{\mathbf{x}}$ the approximate coordinate correction vector of control points, $\mathbf{y}$ the nuisance parameters vector and $\mathbf{v}$ the vector of observation errors. Analytically the equation (1) is given below

$$\begin{aligned}
\mathbf{b}_1 &= \dot{\mathbf{A}}_1\,\dot{\mathbf{x}} + \ddot{\mathbf{A}}_1\,\ddot{\mathbf{x}}_1 + \mathbf{D}_1\,\mathbf{y}_1 + \mathbf{v}_1 \\
\mathbf{b}_2 &= \dot{\mathbf{A}}_2\,\dot{\mathbf{x}} + \ddot{\mathbf{A}}_2\,\ddot{\mathbf{x}}_2 + \mathbf{D}_2\,\mathbf{y}_2 + \mathbf{v}_2 \\
\vdots\ \ & \qquad \vdots \\
\mathbf{b}_\alpha &= \dot{\mathbf{A}}_\alpha\,\dot{\mathbf{x}} + \ddot{\mathbf{A}}_\alpha\,\ddot{\mathbf{x}}_\alpha + \mathbf{D}_\alpha\,\mathbf{y}_\alpha + \mathbf{v}_\alpha
\end{aligned} \tag{2}$$

$$\vdots \qquad \vdots$$

$$\mathbf{b}_m = \dot{\mathbf{A}}_m \, \dot{\mathbf{x}} + \ddot{\mathbf{A}}_m \, \ddot{\mathbf{x}}_m + \mathbf{D}_m \, \mathbf{y}_m + \mathbf{v}_m$$

where the indicator ($_\alpha$) refers to t_α epoch.

The least square criterion, taking into consideration that all the observations are independent for each epoch, is written as

$$\sum_{\alpha=1}^{m} \mathbf{v}_\alpha^T \, \mathbf{P}_\alpha \, \mathbf{v}_\alpha = \text{min.} \tag{3}$$

where $\mathbf{P}_\alpha = \mathbf{Q}_\alpha^{-1}$ is the weight observation matrix of t_α epoch.

The solution is given using the partitioned algorithm adjustment [1], where first the coordinates of reference points are computed and then the coordinates of control points are computed separately for each epoch from the already estimated reference points coordinates.

5. APPLICATION AND RESULTS

In our case an alternative monitoring scheme was followed. Observations between pillars (control and references) consist of slope distances and ellipsoidal height differences which computed from the baseline solutions. The geometrically derived observations from the GPS baseline components (ΔX, ΔY, ΔZ), which contribute to the determination of the horizontal position, are the slope distance S and the geodetic azimuth A computed by [2]

$$S = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \tag{4}$$

$$A = \arctan \frac{-\Delta X \sin\lambda + \Delta Y \cos\lambda}{-\sin\varphi(\Delta X \cos\lambda + \Delta Y \sin\lambda) + \Delta Z \cos\varphi} \tag{5}$$

and reduced properly to the horizontal plane. Considering S and A as synthetic observations for the 2-d net adjustment, the variance – covariance propagation law results in the covariance matrix $\mathbf{C}_{SA}$, which is computed as follows (for more details see [4],[6]):

Linearization

$$\begin{bmatrix} dS \\ dA \end{bmatrix} = \begin{bmatrix} \frac{\partial S}{\partial \Delta X} & \frac{\partial S}{\partial \Delta Y} & \frac{\partial S}{\partial \Delta Z} \\ \frac{\partial A}{\partial \Delta X} & \frac{\partial A}{\partial \Delta Y} & \frac{\partial A}{\partial \Delta Z} \end{bmatrix} \begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix} = \mathbf{L} \begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix} \tag{6}$$

Variance – Covariance propagation law

$$\mathbf{C}_{SA} = \mathbf{L}\,\mathbf{C}_{\Delta X}\,\mathbf{L}^T \tag{7}$$

where,

$$\mathbf{C}_{\Delta X} = \begin{bmatrix} \sigma^2_{\Delta X} & \sigma_{\Delta X \Delta Y} & \sigma_{\Delta X \Delta Z} \\ & \sigma^2_{\Delta Y} & \sigma_{\Delta Y \Delta Z} \\ \text{symmetric} & & \sigma^2_{\Delta Z} \end{bmatrix}$$

In order to test the measurement quality the 2-D free network adjustment of each campaign was applied using as observations the results of the previous analysis and considering the corresponding days as belonging to the same epoch (year). This is usually valid since the time span for each campaign limited to a few consecutive days. For the estimation of displacements a common 2-D network adjustment using all the observations (distances and azimuths) from both GPS campaigns was performed.

To eliminate the differences between the coordinates of the various campaigns due to their different datum definition in each epoch network adjustment, we have used the same approximate coordinate values and we have applied partial inner constrains on the reference points which exists in all (two) GPS campaigns [9]. In addition, proper statistical tests were applied in order to detect possible systematic errors and outliers for each epoch [9],[11],[12]. In table 1 the coordinate displacements with their error ellipses parameters for the control points are presented. The corresponding statistical results are presented in table 2.

Point id	Error Ellipses		Semi major axis azimuth	dx	dy	Displacement $S=\sqrt{dx^2+dy^2}$
	a (cm)	b (cm)	(grad)	(cm)	(cm)	(cm)
1	0.74	0.49	51.34	0.7	0.9	1.1
2	0.74	0.49	46.54	0.6	1.3	1.4
3	0.49	0.49	194.22	0.9	1.4	1.6
4	0.49	0.49	189.86	1.2	2	2.3
5	0.49	0.49	196.54	0.5	1.1	1.2
6	0.49	0.49	26.83	0.9	1.6	1.8
7	0.49	0.25	10.72	1.5	2.2	2.6
8	0.49	0.49	191.07	0.9	3.2	3.3
9	0.74	0.49	60.74	-0.3	0.4	0.6
13	0.49	0.49	195.00	0.9	-0.5	1.0
14	0.49	0.49	194.38	1.6	-0.2	1.6
20	0.74	0.49	29.74	0.3	0.5	0.6
21	0.74	0.49	28.67	0.6	-0.6	1.0
22	0.74	0.74	190.61	0.7	0.2	0.8
25	0.74	0.49	189.78	1.2	-0.3	1.2
26	0.74	0.49	160.93	0.8	-0.1	0.8
27	1.96	1.23	140.12	1.5	-0.5	1.5
28	0.49	0.49	199.41	1.1	0.2	1.1
29	0.74	0.49	24.20	0.2	0.2	0.3
30	0.49	0.49	198.41	-0.2	-0.8	0.8

32	0.98	0.98	147.29	0	1	1.1
33	0.98	0.74	146.38	0.9	-0.2	0.9
39	0.74	0.49	11.49	-0.3	-0.7	0.8

Table 1. Displacements of dam control points and their confidence error ellipses (1-α = 0.95)

GPS Campaign	2003&2005
a-posteriori variance	36.3286
a-posteriori std. deviation	6.03
Degrees of freedom	370

Table 2. A-posteriori parameters of the common adjustment

Analyzing the results of table 1 we can conclude that there is a homogeneous displacements for the control benchmarks which found on the crest dam (id's 1,2,3,4,5,6,7,8), while for the others (on middle and down level, with id's 13,14,22,25,26,27,28,33) there are smaller movements with mainly N-E direction.

In order to estimate the vertical displacements the ellipsoidal height differences which estimated from baseline process were used as observations. This hypothesis can be consider as real because the geoid undulations, between the control points which exist at each leveling traverse were not exceed the 400 meters, in that cases are negligible. The same adjustment steps were followed and the results from the common solution are presented in table 3.

	Difference 2005-2003	Variance	Confidence interval				
Point id	Δh	$\sigma_{\Delta h}$	$\sigma_{\Delta h} t_f^{a/2}$	Point id	Δh	$\sigma_{\Delta h}$	$\sigma_{\Delta h} t_f^{a/2}$
	(cm)	(cm)	(cm)		(cm)	(cm)	(cm)
1	-4.6	0.37	0.60	22	-1.6	0.48	0.79
2	-1.7	0.42	0.69	25	-1.6	0.40	0.66
3	-7.5	0.61	1.01	26	-0.8	0.54	0.90
4	-7.1	0.59	0.97	27	0.3	0.75	1.23
5	-7.6	1.32	2.16	28	0.0	0.33	0.54
6	-2.6	0.64	1.05	29	0.4	0.38	0.62
7	-0.4	0.45	0.74	30	-0.7	0.44	0.73
8	-6.1	0.58	0.95	31	-1.1	0.60	0.98
9	-2.3	0.37	0.60	32	-0.3	0.54	0.89
11	-2.1	0.68	1.11	33	1.0	0.63	1.03
12	-0.5	0.99	1.63	39	0.3	0.43	0.71
13	-0.8	0.50	0.83				

Table 3. Vertical displacements of dam control points and their confidence interval (1-α = 0.95)

6. CONCLUSIONS

In the present study a monitoring technique is performed using geometrically derived observations from the GPS baseline components in Thesarus dam. The observing parameters were distances, azimuths and ellipsoidal height differences from two GPS campaigns. Separate and common 2-D network adjustments were applied for the estimation of horizontal displacements. For the estimation of vertical displacements a 1-D network adjustment is also applied. The result analysis has shown that horizontally there is a homogeneous displacement for most of the control points which is equal to the value of 1 cm. This conclusion can be thought as expected, taking into account the dam structure. As far as the vertical displacements are concerned the results have shown greater values at the order of 3.5 cm. The reference points remain stable despite of their small values. These quantities (<1cm) are under the estimated accuracy and they can be considering as random errors.

Finally, the monitoring of the Thesarus dam, under current circumstances, indicates small or, in other words, expected displacements which confirm its structure stability.

We would like to point out that a new campaign combining GPS and terrestrial data is planning to near future with a re-leveling of GPS benchmarks.

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