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Deformation Measurements and Analysis with Robust Methods: A Case Study, Deriner Dam

Berkant Konakoğlu*, Ertan Gökalp
Karadeniz Technical University, Department of Geomatics, Trabzon, TURKEY
*bkonakoglu@ktu.edu.tr

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Abstract

Dams, one of the country's most natural and cheapest way to product energy, are built for energy production, agricultural activities and flood protection. Dams with high construction costs are subject to deformation due to some physical factors. Therefore, dams should be kept safe to prevent possible dam accidents, loss of life and property. Engineering structures (such as dams) should be monitored periodically by geodetic and non-geodetic techniques. Deriner dam is Turkey's highest double-curved concrete arch dam. In this study, we monitored deformation with GPS measurements. For this purpose, two period static GPS measurements were performed on the reference and object points in the study. Afterwards, GPS measurements were adjusted separately with respect to free adjustment method and then deformation analysis were carried out by using the adjusted coordinates and their cofactor vectors. Iterative Weighted Similarity Transformation (IWST) and Least Absolute Sum (LAS) methods were used as deformation methods to detect the displacement of the reference and object points.

Keywords: Concrete arc dam, Deformation, Analysis, IWST, LAS, GPS.

Deformasyon Ölçmeleri ve Robust Yöntemler ile Analizi: Deriner Barajı Örneği

Özet

Bir ülkenin enerji üretiminin en doğal ve en ucuz yolu olan barajlar enerji üretimi, tarımsal faaliyetler ve taşkın koruma amacıyla inşa edilmektedir. Yapım maliyeti oldukça yüksek olan barajlar çeşitli fiziksel faktörlerinden dolayı deformasyona maruz kalırlar. Olası baraj kazalarını önleyebilmek, can ve mal kaybını önlemek için barajlar güvenlik altında tutulmalıdır. Baraj gibi büyük mühendislik yapıları jeodezik ve jeodezik olmayan yöntemlerle periyodik olarak izlenmelidir. Deriner barajı sahip olduğu gövde yüksekliği ile Türkiye'nin en yüksek çift eğrilikli beton kemer barajıdır. Bu çalışmada deformasyonlar GPS ölçüleri ile belirlenmiştir. Bu amaçla referans ve obje noktalarında iki periyot statik GPS ölçüleri gerçekleştirilmiştir. GPS ölçüleri serbest dengelenerek, dengelenmiş koordinatlar ve kofaktör matrisler kullanılarak deformasyon analizi yapılmıştır. Referans ve obje noktalarındaki hareketleri belirlemek için deformasyon analiz yöntemi olarak İteratif Ağırlıklı Benzerlik Dönüşüm ve En Küçük Mutlak Toplam yöntemleri kullanılmıştır.

Anahtar Kelimeler: Beton Kemer Baraj, Deformasyon, Analiz, IWST, LAS, GPS.

1. Introduction

The dams are one of the most important engineering structures used for water supply, flood protection and agricultural activities. Besides, it is the most natural and cheapest way of energy production for a country. Dams constructed with high cost expenditures are subjected to deformation due to various loading factors such as water level, air, water temperature and rock deformability. Controlling these dams has become compulsory in order to prevent disasters. In the literature, many deformation monitoring based studies have been reported [1]-[8]. Reference [1] investigated the surface movements of Alibey dam by means of geodetic and geotechnical methods. Geodetic displacement measurements were analysed using the Karlsruhe method. Also, Finite Element Method (FEM) was used to determine the behaviour of the dam. The results of geodetic measurements were compared with those of the FEM analyses. Reference [2] examined the long-term settlement behaviour of the Mornos dam in Greece. The result of geodetic monitoring analysis and that of the finite element back analysis were compared. The findings showed a very good agreement between the measured and computed displacements. Reference [3] utilized the Global Positioning System (GPS) technique for monitoring horizontal movements in the Altınkaya dam. A deformation network consisting of 6 reference points and 11 object points along the dam crest were observed for 4 periods. Geodetic displacement measurements were analysed using the IWST and LAS methods to determine the points stability. Reference [4] investigated the magnitude and the direction of radial deformations of the Atatürk dam by means of conventional and GPS techniques. No significant correlation was detected between the radial movements on embankment and reservoir water level. Reference [5] investigated the relationship between displacement and reservoir water levels of the Koyna dam in India by means of GPS technique. The results indicated that a significant correlation between the movements and reservoir water level was detected. Reference [6] evaluated the horizontal movements of the Ermenek dam based on periodic conventional geodetic measurement campaigns during the first filling of the reservoir. Geodetic measurements were compared with those of the FEM. The aim of this work is to investigate the horizontal movements at the Deriner dam with GPS measurements. The coordinates of the GPS measurements are in WGS-84 coordinate system. The coordinates of the points were converted from Cartesian to the local topocentric coordinate system in order to examine the real directions of the displacements. Deformation analysis was performed with the Iterative Weighted Similarity Transformation (IWST) and the Least Absolute Sum (LAS) methods. Finally, the results of these two methods have been compared.

2. Materials and Methods

2.1. Robust Methods

Robust methods are used when there is no previous information about the movement of the points within the network [9]. In this study, the IWST and LAS methods are used to estimate the movements of a monitoring network. The IWST, proposed by [10], is a robust method. According to [11], the Danish, LAS and Huber methods are some of the frequently used robust methods. The IWST and LAS methods are based on S-transformation [10]-[12]. Both methods are applied as follows;

Adjusted coordinates of the points x_1, x_2 and their cofactor matrix Q_{x1}, Q_{x2} are calculated with two separate free adjustments. The displacement values (d) and cofactor matrix of d Q_d are calculated as;

$$d = x_2 - x_1 \tag{1}$$

$$Q_d = Q_{x1} + Q_{x2} \tag{2}$$

Then displacement values (d) are calculated as (3);

$$\begin{aligned} d^{(k+1)} &= \left[I - H\left(H^T W^{(k)} H\right)^{-1} H^T W^{(k)}\right] d^{(k)} \\ &= S^{(k)} d^{(k)} \end{aligned} \tag{3}$$

$\boldsymbol{d}$ = displacement vector

$\boldsymbol{k}$ = number of iterations

$\boldsymbol{I}$ = identity matrix

$\boldsymbol{W}$ = weight matrix

$\boldsymbol{S}$ = S-transformations matrix

H matrix for the 3D networks is written as;

$$H = \begin{bmatrix} e & 0 & 0 & 0 & -z_0 & -y_0 & x_0 \\ 0 & e & 0 & -z_0 & 0 & x_0 & y_0 \\ 0 & 0 & e & y_0 & -x_0 & 0 & z_0 \end{bmatrix}_{3m*7} \tag{4}$$

where, $e^T = (1, \dots \dots \dots, 1)$ x_0, y_0 and z_0 are the coordinates of points P_i, which are reduced to the centre of the network (5).

$$X_0^i = X_i - \frac{1}{m}\sum_{i=1}^{m} x_{i0},$$

$$Y_0^i = Y_i - \frac{1}{m}\sum_{i=1}^{m} y_{i0}, \qquad (5)$$

$$Z_0^i = Z - \frac{1}{m}\sum_{i=1}^{m} z_{i0}$$

Above, z_0^i, y_0^i and x_0^i the i^{th} elements of z^0, y^0 and x^0 respectively, and z_i, y_i and x_i are approximate coordinates of point P_i and m is the number of the points in the network [13]-[15]. The main difference between the IWST and LAS method is in forming the weight matrix. In the first transformation $(k = 1)$ the weight matrix is taken as identity $\left(W^{(k)} = I\right)$ for all common points, then in the (k+1) transformation the weight matrix is defined as;

For the IWST method,

$$W^{(k)} = diag\{1/|d^{(k)}|\} \qquad (6)$$

For the LAS method,

$$W^{(k)} = diag\left\{\frac{1}{\sqrt{(dx_i{}^{(k)})^2 + (dy_i{}^{(k)})^2}}\right\} \qquad (7)$$

In equation (6), d is the displacement vector. However, in equation (7), dx_i and dy_i refer to the displacement components in x and y axis respectively. The iterative procedure continues until the differences between displacements of all common points $\left(d^{(k+1)} - d^{(k)}\right)$ are smaller than a tolarence value Ɛ (i.e. 0.0001 m.). In the final iteration cofactor matrix is calculated as;

$$Q_d^{(k+1)} = S^{(k)} Q_d \left(S^{(k)}\right)^T \qquad (8)$$

The IWST method minimizes the total sum of absolute values of the displacement components,

$$\left(\sum |d_i| \Rightarrow min\right) \qquad (9)$$

while the LAS method minimizes the sum of the lengths of the displacement,

$$\left(\sum \sqrt{(dx_i{}^{(k)})^2 + (dy_i{}^{(k)})^2} \Rightarrow min\right) \qquad (10)$$

Equation (11) can be used in order to determine unstable reference and object points in the deformation network with a single point test as shown below [14];

$$T_i = \frac{\left(d_i^{(k+1)}\right)^T \left(Q_{di}^{(k+1)}\right)^{-1} d_i^{(k+1)}}{u_d \hat{\sigma}_0^2} \sim F(\alpha, u_d, df) \qquad (11)$$

d_i = displacement vector of point i

Q_{di} = cofactor matrix of point i

u_d = dimension of the confidence region (1, 2 or 3)

$\hat{\sigma}_0^2 = \frac{df_i \hat{\sigma}_i^2 + df_j \hat{\sigma}_j^2}{df_i + df_j}$ = pooled variance factor

$\hat{\sigma}_i^2, \hat{\sigma}_j^2$ = a posteriori variance factors of epoch i and j

df_i, df_j = degrees of freedom of epoch i and j

α = significance level

If the test is passed, the point is assumed to be stable, otherwise, it is considered unstable.

3. Application

The Deriner dam, a double-curvature concrete arch dam, is located on the Coruh River at Artvin province in the north-eastern part of Turkey. It is the highest dam with a body height of 249 meters in Turkey. The underground powerhouse near the dam includes four units, with an overall capacity of 670 MW. Also, the powerhouse annually generates 2.118 GWh of electricity. The picture of the dam and technical specifications are given in Figure 1 and in Table 1, respectively.

Figure 1. Deriner dam

Table 1. Technical characteristics of the Deriner dam

Type	Double-curvature concrete arch
Dam crest elevation	397.00 m
Length of dam crest	720.00 m
Height of crest	249.00 m
Total reservoir area	26.40 km^2
Total reservoir volume	1969 hm^3
Electric production capacity	2.117,75 GWh per year

In order to determine the possible horizontal movements on the dam crest, 14 reference and 7 objects points were used (Figure 2).

Figure 2. Distribution of reference and object points in Deriner dam

The deformation measurements of Deriner dam involved two measurement campaigns. The first campaign was carried out in May 2016 and the second one in September 2016. During the GPS measurements, Topcon Hiper Pro and Topcon GR-5 dual-frequencies receivers were used. The observation period was selected as 2 hours and 1.5 hours for reference and object points, respectively. The sampling rate was chosen as 10 seconds and the satellite elevation mask was selected at 15̊. The baselines were processed with the Topcon Tools v.8.2.3 software. MATLAB script was used for network adjustment and deformation analysis. The significance level for deformation detection was specified as 0.05. The adjusted coordinates (WGS-84) and cofactor matrix were obtained from a free network adjustment. Deformation analysis was made with respect to the first period measurement. The two dimensional deformation analysis was made. All WGS-84 coordinates (X, Y, Z) and cofactor matrices were transformed to the local coordinate system (E, N, U). The displacement values (d) were computed by the IWST and LAS methods are shown in Tables 2 and 3. These tables also depicts whether or not the points are stable. Water levels were 389.33 m in the first period and 377.22 m in the second period. The reduction of water level in between the two periods is 12.11 m.

Table 2. Stable and unstable points determined by IWST

Between 1-2 periods				
IWST				
		dN	***dE***	
		cm	***cm***	
Object Points	1139	-0.19	0.18	stable
	1133	0.91	-0.59	unstable
	1127	1.17	-1.15	unstable
	1121	1.09	-1.93	unstable
	1115	0.52	-2.01	unstable
	1109	-0.45	-0.82	unstable
	1103	-0.25	-0.16	stable
Reference Points	105	-0.37	0.53	unstable
	108	0.02	0.24	unstable
	109	-0.09	0.32	unstable
	112	-0.01	-0.12	stable
	118	0.00	0.14	unstable
	101	0.00	-0.03	stable
	102	0.56	0.16	unstable
	104	-0.16	0.47	unstable
	107	-0.13	0	stable
	111	-0.14	0.06	stable
	113	0.01	0.23	stable
	114	0.08	-0.27	stable
	116	0.02	-0.13	stable
	117	-0.14	0.24	unstable

Table 3. Stable and unstable points determined by LAS

	Between 1-2 periods			
	LAS			
		dN	*dE*	
		cm	*cm*	
Object Points	1139	-0.17	0.17	stable
	1133	0.93	-0.61	unstable
	1127	1.19	-1.16	unstable
	1121	1.11	-1.93	unstable
	1115	0.53	-2.00	unstable
	1109	-0.43	-0.82	unstable
	1103	-0.24	-0.17	stable
Reference Points	105	-0.35	0.52	unstable
	108	0.04	0.23	unstable
	109	-0.07	0.31	unstable
	112	0.00	-0.13	stable
	118	0.02	0.14	stable
	101	0.03	-0.02	stable
	102	0.59	0.17	unstable
	104	-0.13	0.47	unstable
	107	-0.11	0.00	stable
	111	-0.13	0.06	stable
	113	0.04	0.23	stable
	114	0.12	-0.26	stable
	116	0.05	-0.13	unstable
	117	-0.12	0.24	unstable

4. Conclusion

Since we have no prior information about the movement of the points within the network, the IWST and LAS methods were used in this study. The IWST and LAS were used to perform 2D deformation analysis. It can be concluded from the results of the analysis that the displacements are dependent on the water level on the reservoir. The maximum horizontal displacement was experienced in the middle of the dam crest. These results will also be examined with new measurements to be conducted in further periods. Also, precise differential levelling of levelling line along the dam crest will be performed.

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