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 arch dam, Deformation, Analysis, 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

Deformasyon Ölçmeleri ve Robust Yöntemler ile Analizi: Deriner Barajı Örneği

Özet


Anahtar Kelimeler: Beton Kemer Barajı, Deformasyon, Analiz, IWST, LAS, GPS.
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);

\[
d^{(k+1)} = \left[ I - H^{(k)}(H^{(k)}W^{(k)}H)^{-1}H^{(k)}W^{(k)} \right]d^{(k)}
\]

\[
= S^{(k)}d^{(k)}
\]

\( d = \) displacement vector
\( k = \) number of iterations
\( I = \) identity matrix
\( W = \) weight matrix
\( S = \) S-transformations matrix

H matrix for the 3D networks is written as;

\[
H = \begin{bmatrix}
e & 0 & 0 & -z_0 & -y_0 & x_0 \\
e & 0 & -z_0 & 0 & x_0 & y_0 \\
0 & e & y_0 & -x_0 & 0 & z_0_j \end{bmatrix}
\]

where, \( e^T = (1, \ldots, 1) \) \( x_0, y_0 \) and \( z_0 \) are the coordinates of points \( P_i \), which are reduced to the centre of the network (5).
\[
X^i_0 = X_i - \frac{1}{m} \sum_{i=1}^{m} x_{i0} \]
\[
Y^i_0 = Y_i - \frac{1}{m} \sum_{i=1}^{m} y_{i0} \quad (5)
\]
\[
Z^i_0 = Z - \frac{1}{m} \sum_{i=1}^{m} z_{i0}
\]

Above, \(z^i_0, y^i_0, \) and \(x^i_0\) are 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 \((W^{(k)} = I)\) for all common points, then in the \((k+1)\) transformation the weight matrix is defined as:

For the IWST method,

\[
W^{(k)} = diag \{1/|d^{(k)}|\} \quad (6)
\]

For the LAS method,

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

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 \((d^{(k+1)} - d^{(k)})\) are smaller than a tolerance value \(E\) (i.e. 0.0001 m.). In the final iteration cofactor matrix is calculated as;

\[
Q_{d}^{(k+1)} = S^{(k)} Q_d (S^{(k)})^T \quad (8)
\]

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

\[
(\sum |d_i| \Rightarrow \text{min}) \quad (9)
\]

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

\[
(\sum \sqrt{(dx_i^{(k)})^2 + (dy_i^{(k)})^2} \Rightarrow \text{min}) \quad (10)
\]

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]:

\[
T_i = \frac{(d_i^{(k+1)})^T (Q_{di}^{(k+1)})^{-1} d_i^{(k+1)}}{u_d \sigma_0^2} \sim F(a, u_d, df) \quad (11)
\]

\(d_i\) = displacement vector of point \(i\)
\(Q_{di}\) = cofactor matrix of point \(i\)
\(u_d\) = dimension of the confidence region (1, 2 or 3)
\(\sigma_0^2\) = pooled variance factor
\(\sigma_i^2, \sigma_j^2\) = a posteriori variance factors of epoch \(i\) and \(j\)
\(df_i, df_j\) = degrees of freedom of epoch \(i\) and \(j\)
\(\alpha\) = 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

<table>
<thead>
<tr>
<th>Type</th>
<th>Double-curvature concrete arch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam crest elevation</td>
<td>397.00 m</td>
</tr>
<tr>
<td>Length of dam crest</td>
<td>720.00 m</td>
</tr>
<tr>
<td>Height of crest</td>
<td>249.00 m</td>
</tr>
<tr>
<td>Total reservoir area</td>
<td>26.40 km²</td>
</tr>
<tr>
<td>Total reservoir volume</td>
<td>1969 hm³</td>
</tr>
<tr>
<td>Electric production capacity</td>
<td>2.117,75 GW h per year</td>
</tr>
</tbody>
</table>

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 15. 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 matrices 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

<table>
<thead>
<tr>
<th>Object Points</th>
<th>dN (cm)</th>
<th>dE (cm)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1139</td>
<td>-0.19</td>
<td>0.18</td>
<td>stable</td>
</tr>
<tr>
<td>1133</td>
<td>0.91</td>
<td>-0.59</td>
<td>unstable</td>
</tr>
<tr>
<td>1127</td>
<td>1.17</td>
<td>-1.15</td>
<td>unstable</td>
</tr>
<tr>
<td>1121</td>
<td>1.09</td>
<td>-1.93</td>
<td>unstable</td>
</tr>
<tr>
<td>1115</td>
<td>0.52</td>
<td>-2.01</td>
<td>unstable</td>
</tr>
<tr>
<td>1109</td>
<td>-0.45</td>
<td>-0.82</td>
<td>unstable</td>
</tr>
<tr>
<td>1103</td>
<td>-0.25</td>
<td>-0.16</td>
<td>stable</td>
</tr>
<tr>
<td>105</td>
<td>-0.37</td>
<td>0.53</td>
<td>unstable</td>
</tr>
<tr>
<td>108</td>
<td>0.02</td>
<td>0.24</td>
<td>unstable</td>
</tr>
<tr>
<td>109</td>
<td>-0.09</td>
<td>0.32</td>
<td>unstable</td>
</tr>
<tr>
<td>112</td>
<td>-0.01</td>
<td>-0.12</td>
<td>stable</td>
</tr>
<tr>
<td>118</td>
<td>0.00</td>
<td>0.14</td>
<td>unstable</td>
</tr>
<tr>
<td>101</td>
<td>0.00</td>
<td>-0.03</td>
<td>stable</td>
</tr>
<tr>
<td>102</td>
<td>0.56</td>
<td>0.16</td>
<td>unstable</td>
</tr>
<tr>
<td>104</td>
<td>-0.16</td>
<td>0.47</td>
<td>unstable</td>
</tr>
<tr>
<td>107</td>
<td>-0.13</td>
<td>0</td>
<td>stable</td>
</tr>
<tr>
<td>111</td>
<td>-0.14</td>
<td>0.06</td>
<td>stable</td>
</tr>
<tr>
<td>113</td>
<td>0.01</td>
<td>0.23</td>
<td>stable</td>
</tr>
<tr>
<td>114</td>
<td>0.08</td>
<td>-0.27</td>
<td>stable</td>
</tr>
<tr>
<td>116</td>
<td>0.02</td>
<td>-0.13</td>
<td>stable</td>
</tr>
<tr>
<td>117</td>
<td>-0.14</td>
<td>0.24</td>
<td>unstable</td>
</tr>
</tbody>
</table>
Table 3. Stable and unstable points determined by LAS between 1-2 periods.

<table>
<thead>
<tr>
<th>Object Points</th>
<th>LAS</th>
<th>Reference Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1139</td>
<td>-0.17</td>
<td>-0.17</td>
</tr>
<tr>
<td>1133</td>
<td>0.93</td>
<td>-0.61</td>
</tr>
<tr>
<td>1127</td>
<td>1.19</td>
<td>-1.16</td>
</tr>
<tr>
<td>1121</td>
<td>1.11</td>
<td>-1.93</td>
</tr>
<tr>
<td>1115</td>
<td>0.53</td>
<td>-2.00</td>
</tr>
<tr>
<td>1109</td>
<td>-0.43</td>
<td>-0.82</td>
</tr>
<tr>
<td>1103</td>
<td>-0.24</td>
<td>-0.17</td>
</tr>
<tr>
<td>105</td>
<td>-0.35</td>
<td>0.52</td>
</tr>
<tr>
<td>108</td>
<td>0.04</td>
<td>0.23</td>
</tr>
<tr>
<td>109</td>
<td>-0.07</td>
<td>0.31</td>
</tr>
<tr>
<td>112</td>
<td>0.00</td>
<td>-0.13</td>
</tr>
<tr>
<td>118</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>101</td>
<td>0.03</td>
<td>-0.02</td>
</tr>
<tr>
<td>102</td>
<td>0.59</td>
<td>0.17</td>
</tr>
<tr>
<td>104</td>
<td>-0.13</td>
<td>0.47</td>
</tr>
<tr>
<td>107</td>
<td>-0.11</td>
<td>0.00</td>
</tr>
<tr>
<td>111</td>
<td>-0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>113</td>
<td>0.04</td>
<td>0.23</td>
</tr>
<tr>
<td>114</td>
<td>0.12</td>
<td>-0.26</td>
</tr>
<tr>
<td>116</td>
<td>0.05</td>
<td>-0.13</td>
</tr>
<tr>
<td>117</td>
<td>-0.12</td>
<td>0.24</td>
</tr>
</tbody>
</table>

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.

5. Acknowledgment

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6. References