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Full Length Research Paper

Analysis of dam deformation measurements with the robust and non-robust methods

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Rapid developments in engineering structures, the growing interest in studying the earth crust movements, the analysis of deformation measurements, measurement methods and precision have revealed new demands. The purpose of this study is to determine the deformations that take place on dam crest due to different water level, load and dam's body weight. Altinkaya Dam, which is a rock fill dam, was selected as application area and a deformation network consisting of 6 references and 11 object points were constructed. In this study, deformation measurements were performed between 2000 and 2002. Measurements were made every June and September, in that the water level was minimum and maximum, respectively. Hence, measurements were made in 4 periods. All measurements were performed using static GPS measurement method. In this study, Iterative weighted transformation (IWST), Least Absolute Sum (LAS), Congruency test analysis method and Fredericton were used for performing two dimensional deformation analyses.

Key words: GPS, dam, deformation, analysis, congruency test, IWST, LAS, Fredericton.

INTRODUCTION

The fast developments in the technological and scientific fields have begun to manifest in different engineering structures, such as skyscrapers, long bridges, nuclear power plants, hydroelectric plants, rock fill and concrete dams, high viaducts e.t.c. Huge increases in the growth of engineering structures are required in monitoring of these structures. Particularly, monitoring of these structures in the earthquake fault zones is more important.

These developments in technological and scientific fields have led to the development in the analysis methods and evaluation of measurements instruments used in the monitoring of deformations of engineering structures. In recent years, the development of geodetic deformation measurement and evaluation methods has been very impressive. Global positioning systems (GPS), laser scanning, robotic total stationlar are some of the technological development in this profession.

In the studies in engineering structures, selection of measuring instruments and observation techniques depend on the rate and magnitude of deformation. To ensure a strong foundation of collecting data for deformation analysis, measurable items must benefit from the new technologies and all types of measurements in the deformation observation network are combined. Generally, at the deformation analysis, interests are in small amount of deformations in the limits of measurement errors. To give correct decisions about the accepting of deformation model, very carefully done accurate analysis and statistical test of the results are required (Taşçi, 2003). The electric power in Turkey is to a large extent generated from the water temporarily stored in reservoirs. Deformations of points on dam crest have so far mainly been defined by geodetic measurements.

The purpose of this work is to monitor and analyze the deformations at the crest of the Altınkaya Dam which were caused by the water load at different levels combined with the dam's weight. A secondary goal was using of the different analysis methods and to determine whether GPS measurements could meet the accuracy requirements for dam deformation measurements. In this study, Iterative weighted transformation (IWST), Least Absolute Sum (LAS), Congruency test analysis method and Fredericton are used. At the work field, rock fill Altınkaya Dam, one of the highest dams in Turkey is selected and GPS deformation measurements in this dam are used to perform analysis.

ROBUST AND NON-ROBUST METHODS FOR ANALYZING OF THE DISPLACEMENTS

In this work, for the determination of displacements of deformation, monitoring networks are used- IWST, LAS robust methods with congruency testing and Fredericton non-robust methods.
Robust methods are used when there is no previous information about the movement of points within the network (Chen, 1983; Singh and Setan, 1999, 1999/1, 2001).

Congruency testing and Fredericton are known as non-robust method. These methods have been applied to estimate the displacements of all common points in a deformation network.

Being different from robust methods of congruency testing, congruency testing will iteratively remove one datum point at a time until the congruency test is passed (Singh and Setan 2001).

The Fredericton approach determines the unstable points within the network by analyzing the changes (Δl) in length and/or angle between two measurement periods which are derived from a least squares adjustment of coordinates (Gökalp and Taşçi, 2009; Chrzanowski and Chen, 1986; Chen et al., 1990).

Necessity of a pre-transformation

Adjusted coordinates of the points $\hat{x}_1, \hat{x}_2$ in the deformation network and their cofactor (covariance) matrices $Q_{\hat{x}1}, Q_{\hat{x}2}$ are calculated with two separate adjustments.
Displacement values (d) and the cofactor matrix of d Q_d are calculated as:

$$d = \hat{x}_2 - \hat{x}_1 \quad (1)$$

$$Q_d = Q_{\hat{x}1} + Q_{\hat{x}2} \quad (2)$$

Displacement values (d) are calculated from equation 3:

$$d = S(W)d \quad (3)$$

Here, S(W) shows that S matrix, calculated with W=I, can be obtained as (Setan and Singh, 1998; Chen, 1983; Chrzanowski et al., 1986; Singh and Setan 2001):

$$S = \left(I - H\left(H^T WH\right)^{-1} H\right]^T W\right) \quad (4)$$

where the H matrix for the 3D network is written as:

$$H = \begin{bmatrix} e & 0 & 0 & 0 & z_0 & -y_0 & x_0 \\ 0 & e & 0 & -z_0 & 0 & x_0 & y_0 \\ 0 & 0 & e & y_0 & -x_0 & 0 & z_0 \end{bmatrix}_{3m*7} \quad (5)$$

eT = (1,..........1)

y_i^0, x_i^0 are approximate coordinate vectors with respect to the centre of the network and this approximate coordinates are calculated as:

$$X_0^i = X_i - \frac{1}{m}\sum_1^m X_{i0}$$
$$Y_0^i = Y_i - \frac{1}{m}\sum_1^m Y_{i0} \quad (6)$$
$$Z_0^i = Z_i - \frac{1}{m}\sum_1^m Z_{i0}$$

Here, y_i, x_i are approximate coordinate of point Pi and m is the number of the points in the network (Kuang, 1996; Öztürk and Şerbetçi, 1992; Singh and Setan, 2001).

ROBUST ESTIMATION PROCEDURE

IWST (Iterative Weighted Similarity Transformation Method)

A method to detect unstable reference points has been developed which is based on a special similarity transformation that minimizes the first norm (absolute value) of the observed vector of displacements of the reference points. The IWST approach to stability monitoring can be performed easily for one-dimensional reference networks and by an iterative weighting scheme for multi-dimensional reference networks until all the components of the displacement vectors (d i) satisfy the condition: ∑ || d i || = minimum.

According to Chen (1983), a datum and robust methods are used in determining unstable points. Determining results with this method are really deformation model (EM.1110-2-1009, 2002). Calculated displacement values could be affected from datum selecting or from defining two different data while adjusting the measurements taken at two different periods. Therefore, the weight matrix is obtained iteratively.

Further details can be found (Chen, 1983; Chen et al., 1990; Setan and Singh, 1998; Taşçi, 2003, 2008; Gökalp and Taşçi, 2009).

LAS (least absolute sum)

According to Singh and Setan (2001), details of this method are given by Caspary and Borutta. In the LAS methods, some points in a reference network cannot be accepted as stable. In other words, not every point has equal importance. Hence, in the beginning, the weight matrix (W) is accepted as W = I. While datum determines, this indicates that all the points in the network have the same importance. Therefore, the solution is similar to the Helmert transformation, if some points are given unit weight and the others a zero weight, that is,, W = diag {I, 0}.

Further details can be found in Singh and Setan (2001, 1998, 1999, 1999/1) and Taşçi (2008).

The IWST and LAS methods are used when there is no previous information about the movement of points within the network.

NON-ROBUST ESTIMATION PROCEDURE

Congruency testing

Non-robust method is known as congruency testing. This method is applied for determining displacements of all points in the monitoring networks. Being different from robust methods, congruency testing will iteratively remove one datum point at a time until the test is passed. General procedure of congruency testing is given as:

1. For both epochs in a common datum, displacement vectors (d) and its Cofactor matrix (Q_d) are determined.
2. Stable points are determined by congruency testing.
3. Localization of deformations by single point test is determined by S transformation and congruency test.
4. The final testing of deformations is performed by single point test.

Transformation of both epochs in a common datum

During deformation analysis by congruency test, displacement vector d and its cofactor matrix Q_d are important to refer to the same datum. In this study, S transformation has been applied to transform matrix d and Q_d into a common datum.

$$d_1 = S * d \tag{7}$$

$$Qd_1 = S * Q_d * S^T \tag{8}$$

$$S = \left(I - H\left(H^T WH\right)^{-1} H\right]^T W\right) \tag{9}$$

Where d_1 is displacement vector and Q_{d1} is its cofactor matrix. H is datum defect matrix and W is weight matrix.

Congruency testing on the selected datum points

Congruency testing is performed to determine whether selected datum points have significantly moved between the two epochs.

Null and alternative hypotheses for congruency testing (Singh and Setan, 2001) are seen below:

H_0 : E(d_1') = 0 No significant deformation for a group of datum points

H_0 : E(d_1') ≠ 0 Existence of significant deformation for a group of datum points

The test statistic:

$$w = \frac{d_1'^T Q_{d1}'^{+} d_1'}{h\left(\widehat{\hat{\sigma}_0^2}\right)} \approx F(\alpha, h, d_f) \tag{10}$$

$$h = rank(Q'_{d1}) = (2n - d) \tag{11}$$

$\hat{\sigma}_0^2$ = variance factor

$(Q_{d1}'^{+})$= pseudo inverse

α= 0.05 significant level

If the test statistic does not exceed the critical value of the F distribution, Hypothesis is accepted in the significant level (α). If the test statistic exceeds $\left(w < F(\alpha, h, d_f)\right)$ the critical value of the F distribution, hypothesis is rejected in the significant level (α). The rejection of hypothesis indicates the existence of deformation in a group of points or in the points in the network. The network is transformed into a new computational base. This procedure continues until all of the remaining points were verified as stable by congruency test.

Single point test on the objects points

Purpose of single point test is localization of point with largest statistical value. This point will be eliminated in the datum or at the computational base (Singh and Setan, 2001).

$$T_j = \frac{d_1'^T Q_{d1}'^{-1} d_{1j}'}{2\left(\widehat{\sigma_0^2}\right)} \tag{12}$$

where (d'_{ij}) displacement vectors and (Q'_{dij}) cofactor matrix of every j point.

Point with the largest Tj value causes changes in the form of network. So, this point will be eliminated from the computational base. Later, network will continue by new computational base with the remaining points.

Transformation of network into new computational base

$$d_2 = S * d \tag{13}$$

$$Qd_2 = S * Q_d * S^T \tag{14}$$

$$S = \left(I - H\left(H^T WH\right)^{-1} H\right)^T W \quad (15)$$

Where $(d_2 \text{ and } Q_{d2})$ are respectively displacement vectors and cofactor matrix of every j point. W is weighted matrix (for remaining datum points are diagonal value 1 and other zero)

Congruency test on the remaining points

Statistical test is equal equation but only remaining points are applied. Hypothesis for this test is given below.
H_0: $E(d_2') = 0$ No significant deformation for a group of datum points
H_0: $E(d_2') \neq 0$ Existence of significant deformation for a group of datum points

$$W = \frac{d_2'^T Q_{d2}'^{+} d_2'}{h - 2k * (\sigma_0^2)} \approx F(\propto, h - 2k, d_f) \quad (16)$$

If the test statistic exceeds $(w \geq F(\alpha, h - 2k, d_f))$ the critical value of the F distribution, hypothesis is rejected in the significant level (α). If the test statistic does not exceed the critical $(w \geq F(\alpha, h - 2k, d_f))$ value of the F distribution, hypothesis is accepted in the significant level (α) and all of the points in the network are determined as the stable.

Deformation result test by the single point test

H_0: $d_{2i} = [dx_{2i}\ dy_{2i}]^T = 0$ No significant deformation for a group of datum points
H_0: $d_{2i} = [dx_{2i}\ dy_{2i}]^T \neq 0$ Existence of significant deformation for a group of datum points.
Test statistic:

$$T_j = \frac{d_2'^T Q_{d2}'^{-} d_2'}{2(\sigma_0^2)} \approx F(\propto, 2, d_f) \quad (17)$$

In the above given test, if the test $(w < T_j(\alpha, 2, d_f))$ passes the significant level (α), then, j point is considered as the stable. Otherwise, the test data at the point j are considered to be a significant deformation. In the result, if any point still appears to be moving, point with the largest statistical value is eliminated. Localization process continues.

Fredericton approach

In order to analyze deformation measurements, a generalized approach has been developed by the Fredericton group. The approach is applicable to any type of geometrical analysis, both in space and in time domains. Additionally, it can be used for the detection of unstable points in reference networks and the determination of strain components and relative rigid body motions in relative networks (Chizanowski and Chen, 1986).

The Fredericton approach determines the unstable points within the network by analyzing the changes (Δl) in length and/or angle between two measurement periods which are derived from a least squares adjustment of coordinates.

Further details can be found in Chrzanowski and Chen (1986, 1983, 1990) and Taşçi (2003, 2008).

APPLICATION

Definition of work area

Altınkaya Dam is 35 km south west of the Bafra, Samsun. This dam is structured by one of the Turkish Government establishments that is called State Hydraulic Works. Altinkaya Dam is 22nd among rock fill large dams in Turkey and also it is 32nd dams in the world. The dam is built on the Kizlirmak River as rock fill with clay having seeds. Height of the dam (from river bed) is 195.0 m. and crest length is 634.0 m. Reservoir area at normal water surface elevation is 118.31 km2. Volume of the dam is 16 x 106 m³. The dam is convex towards the water.

Measurement and building of monument of reference and object points

Monitoring network consists of six reference stations (1001, 1002, 1003, 1004, 1005 and 1006); they were built as pillars on the stable ground which surrounds the dam. In order to monitor and measure possible displacements at the crest, 10 object points were established at the crest when the dam was built (Figure 1). Since that time only one object point, numbered 0023, was added to the deformation network. This point was built because of the physical changes that had been observed in the surrounding area. The deformation measurements related to the reference and object network were made with 3 Ashtech Z surveyor GPS receivers and 700700B_Mar.III_L1/L2 GPS antennas.

Deformation measurements started on 21.09.2000. Later deformation measurements are realized in months expecting to be maximum and minimum of dam reservoir water level (Table 1).

For the deformation measurements, two different measurement plans were applied to the survey object points. In the first plan, two receivers were set over points 1003 and 1004. Then, the third receiver was set over each object point about 30 min. In the second plan, a

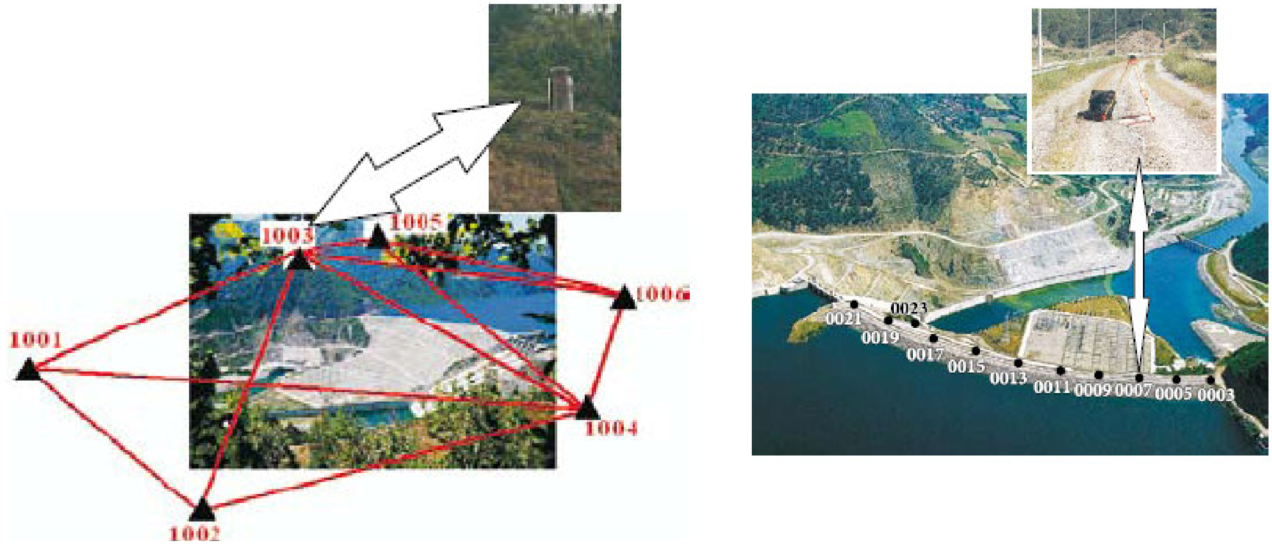

Figure 1. Deformation network.

Table 1. Information related to the deformation network.

Period No	Measurement date	Water level(m)
1	21/09/2000	170.34
2	05/06/2001	167.53
3	20/09/2001	164.20
4	27/05/2002	177.23

receiver was set over point 0003 during the observation periods, and the other points were measured using a leapfrog method. The main goal of this measurement plan was to correlate the observations and make loop closures. The object point measurements were taken using tripods with optical plummets and string plumb-bobs used for centering. Before commencing deformation measurements, all the equipment was calibrated. In order to avoid or diminish any equipment errors the same GPS receivers and antennas were used at the same points in all periods.

Baseline lengths in the deformation network are changing between 60 m and 2 km. The measurements related to reference network were made with 3 GPS receivers. Observation period was 45 min with sampling rate of 10 s in reference network. Satellite elevation mask was selected at 15^o in order to reduce multipath effect and cycle slip error.

Processing of the GPS observations

Deformation network was processed with GeoGenious 2000 software. The baselines were processed accurately at maximum of 0.9 mm horizontally and 1.7 mm vertically for 4 periods of observations. Point coordinates E, N and their cofactor matrices Q_{x1}, Q_{x2} were calculated with two separate free network adjustments. Variances obtained from free network adjustment respectively are 1.062, 0.787, 0.813 and 0.620. In order to determine the gross error of the baseline measurements, Tau test was used.

The Minimum Norm Quadratic Unbiased Estimation (MINQUE) method was used to determine the accuracy of the baseline measurements instead of taking the values that are given by the GPS receiver and software manufacturers. The accuracy of baselines was calculated 4 mm horizontally and 6 mm vertically by MINQUE (Taşçi, 2003; Taşçi and Gökalp, 2002).

In this work, only horizontal displacements were determined and analyzed. In order to see real direction of the obtained displacement, all WGS 84 coordinates were transformed to local topocentric coordinate system (Taşçı, 2003, 2008)

DETERMINATION OF STABLE AND UNSTABLE POINTS IN THE DEFORMATION NETWORK

In the process, determination of movement points in the network with IWST, LAS and Congruency Test method for each period is tested according to α = 0.95.

Fredericton method for each period is tested according to α = 95%, α = 0.97.5% and α = 99%.

First period is taken as the reference period. Therefore, reference period is formed as 1 - 2, 1 - 3, 1 – 4 periods. In determining the displacement values (d) with IWST, LAS, Congruency test method and Fredericton are given in Tables 2, 3, 4 5 and 6.

Water levels were 170.34 m in first period, 167.53 m – in the second period, 164.20 m – in the third period, and

Table 2. Stable and unstable points determined using IWST (Taşçı, 2003, 2008; Gökalp and Taşçı, 2009).

	Points	Stable and unstable points determined using IWST											
		Between 1-2 Periods				Between 1-3 periods				Between 1 - 4 periods			
		dN (mm)	dE (mm)	Displacement dN	Displacement dE	dN (mm)	dE (mm)	Displacement dN	Displacement dE	dN (mm)	dE (mm)	Displacement dN	Displacement dE
Reference points	1001	-4.9	1.0	Stable	Stable	2.9	9.7	Stable	Unstable	-5.7	-0.6	Stable	Stable
	1002	0.0	4.8	Stable	Unstable	-10.3	5.2	Unstable	Stable	-1.3	-1.1	Stable	Stable
	1003	0.1	0.0	Stable	Stable	2.1	0.0	Stable	Stable	-0.9	2.3	Stable	Stable
	1004	-2.3	0.0	Stable	Stable	-1.7	-0.7	Stable	Stable	1.4	-2.8	Stable	Stable
	1005	-3.5	0.0	Stable	Stable	2.4	-1.4	Stable	Stable	-1.8	1.4	Stable	Stable
	1006	-6.2	2.6	Unstable	Stable	-7.0	0.2	Unstable	Stable	0.1	0.0	Stable	Stable
Object points	0003	3.9	-4.9	Stable	Unstable	6.4	-5.0	Unstable	Unstable	7.5	-4.2	Unstable	Stable
	0005	1.8	-1.2	Stable	Stable	4.6	1.5	Stable	Stable	4.7	-0.7	Stable	Stable
	0007	4.6	0.0	Unstable	Stable	5.8	-2.9	Unstable	Stable	4.2	1.8	Unstable	Stable
	0009	4.9	0.0	Stable	Stable	3.3	-1.7	Stable	Stable	7.6	2.6	Unstable	Stable
	0011	4.4	3.6	Unstable	Unstable	7.5	0.3	Stable	Stable	3.1	10.0	Stable	Unstable
	0013	-2.4	4.7	Stable	Unstable	-1.8	3.1	Stable	Stable	-2.9	7.3	Stable	Unstable
	0015	0.0	-2.7	Stable	Stable	0.0	-6.0	Stable	Unstable	1.0	-4.5	Stable	Unstable
	0017	0.0	-2.5	Stable	Stable	-5.3	2.2	Unstable	Stable	-2.8	1.9	Stable	Stable
	0019	-4.8	-4.3	Unstable	Unstable	-7.6	-1.0	Unstable	Stable	-5.4	-3.0	Unstable	Stable
	0021	0.0	0.0	Stable	Stable	-2.1	1.0	Stable	Stable	-0.5	-3.3	Stable	Stable
	0023	2.1	-4.5	Stable	Stable	-1.7	-4.5	Stable	Stable	-1.0	-2.2	Stable	Stable

177.23 m – in the final period. Between 3 epochs observed, because of a larger electric production and no rainfall, water level has decreased. The reduction of water level in between the 3 epochs is 6.14 m. This reduction caused the movement of points on the dam's crest. These horizontal movements on the crest that could occur in the middle of the dam crest in arch dams were proved by the GPS measurements and deformation analysis methods.

The maximum deformation is expected in the middle parts of the crest in arch dams. Toward two ends of the crest, it is expected that the deformation is minimum. Consequently, in this work, same kind of result has been found because mainly significant movements have been seen in points 0011 and 0013 which are in the middle parts of the dam's crest.

Stable and unstable points determined by IWST, LAS, Congruency test and Fredericton are given in Table 7.

Conclusion

In this work, hypothesis that maximum horizontal movements caused by water load effect could occur in the middle of the dam's crest in arch dams was approved by applied GPS measurements and deformation analysis methods.

When formulas and computational base including displacement testing consider, congruency test is more complex than robust methods. Robust methods and congruency test are important computational bases used in the determination of displacements of all the points in the network.

The selection process of the unstable point/points became less conclusive when the repetition of the failure was similar for most of the points in the Fredericton method. This requires interpret-

Table 3. Stable and unstable points determined using LAS (Taşçı, 2003, 2008).

	Points	Stable and unstable points determined using LAS											
		Between 1-2 Periods				Between 1-3 Periods				Between 1-4 Periods			
		dN (mm)	dE (mm)	Displacement dN	Displacement dE	dN (mm)	dE (mm)	Displacement dN	Displacement dE	dN (mm)	dE (mm)	Displacement dN	Displacement dE
Reference points	1001	-4.8	1.6	Unstable	Stable	2.9	10.5	Stable	Unstable	-5.0	-0.2	Unstable	Stable
	1002	0.3	5.5	Stable	Unstable	-10.3	6.1	Unstable	Stable	-1.0	-0.9	Stable	Stable
	1003	1.1	0.9	Stable	Stable	2.3	0.7	Unstable	Stable	-0.9	3.4	Stable	Stable
	1004	-2.1	1.5	Stable	Stable	-1.5	0.0	Stable	Stable	0.9	-2.5	Stable	Stable
	1005	-3.3	0.4	Stable	Stable	2.6	-0.8	Stable	Stable	-2.3	2.8	Stable	Stable
	1006	-5.9	3.2	Unstable	Stable	-6.8	1.0	Unstable	Stable	-0.6	0.7	Stable	Stable
Object points	0003	4.3	-4.3	Stable	Unstable	6.6	-4.2	Unstable	Unstable	7.4	-3.5	Unstable	Unstable
	0005	2.2	-0.6	Stable	Stable	4.8	2.3	Unstable	Stable	4.5	-0.1	Unstable	Stable
	0007	4.9	1.0	Unstable	Stable	6.1	-2.1	Unstable	Stable	4.1	2.5	Unstable	Stable
	0009	5.2	0.4	Unstable	Stable	3.6	-0.9	Stable	Stable	7.5	3.2	Unstable	Stable
	0011	4.7	4.2	Unstable	Unstable	7.7	1.2	Unstable	Stable	3.0	0.6	Unstable	Unstable
	0013	-2.1	5.3	Stable	Unstable	-1.6	3.9	Stable	Stable	-3.5	7.7	Unstable	Unstable
	0015	0.6	-2.2	Stable	Stable	0.4	-5.3	Stable	Unstable	0.2	-4.4	Stable	Unstable
	0017	0.3	-1.9	Stable	Stable	-5.2	3.0	Unstable	Stable	-3.7	2.6	Unstable	Unstable
	0019	-4.5	-3.8	Unstable	Unstable	-7.4	-0.2	Unstable	Stable	-5.8	-2.4	Unstable	Stable
	0021	-0.3	0.9	Stable	Stable	-1.9	1.9	Stable	Stable	0.4	-2.7	Stable	Stable
	0023	2.4	-3.9	Stable	Unstable	-1.5	-3.8	Stable	Stable	-1.1	-1.9	Stable	Stable

Table 4. Stable and unstable points determined using congruency method.

	Points	Stable and unstable points determined											
		Between 1 - 2 periods				Between 1 - 3 periods				Between 1 - 4 periods			
		dN (mm)	dE (mm)	Disp. vector (mm)	Displacement	dN (mm)	dE (mm)	Disp. vector (mm)	Displacement	dN (mm)	dE (mm)	Disp. vector (mm)	Displacement
Reference points	1001	-4.7	1.1	4.82	Stable	3.4	9.7	10.29	Unstable	-5.3	-1.1	5.40	Unstable
	1002	0.3	4.9	4.94	Stable	-10.1	5.2	11.34	Unstable	-1.3	-1.8	2.17	Stable
	1003	1.0	0.6	1.12	Stable	2.3	0.2	2.32	Stable	-1.1	2.5	2.77	Stable
	1004	-2.3	1.0	2.51	Stable	-1.7	-0.8	1.92	Stable	0.7	-3.3	3.41	Stable
	1005	-3.5	0.1	3.51	Stable	2.5	-1.2	2.75	Stable	-2.5	1.9	3.15	Stable
	1006	-6.2	2.7	6.79	Unstable	-7.1	0.2	7.14	Stable	-0.8	-0.2	0.84	Stable

Table 4 Contd.

Object points	0003	4.1	-4.8	6.31	Unstable	6.6	-5.0	8.24	Unstable	7.2	-4.3	8.39	Unstable
	0005	2.0	-1.1	2.28	Stable	4.8	1.6	5.02	Stable	4.3	-1.0	4.40	Unstable
	0007	4.7	0.5	4.77	Unstable	6.0	-2.9	6.64	Unstable	3.8	1.6	4.15	Unstable
	0009	5.0	-0.1	5.04	Unstable	3.5	-1.7	3.88	Stable	7.2	2.3	7.60	Unstable
	0011	4.5	3.7	5.87	Unstable	7.7	0.4	7.67	Stable	2.7	9.7	10.06	Unstable
	0013	-2.3	4.8	5.34	Unstable	-1.7	3.1	3.54	Stable	-3.7	6.8	7.79	Unstable
	0015	0.4	-2.7	2.68	Stable	0.4	-6.1	6.13	Unstable	0.0	-5.3	5.29	Unstable
	0017	0.1	-2.4	2.45	Stable	-5.3	2.2	5.70	Unstable	-3.9	1.7	4.26	Unstable
	0019	-4.7	-4.3	6.38	Unstable	-7.5	-1.1	7.56	Unstable	-6.0	-3.3	6.84	Unstable
	0021	-0.5	0.4	0.65	Stable	-2.0	1.0	2.22	Stable	0.1	-3.5	3.54	Stable
	0023	2.2	-4.4	4.97	Stable	-1.6	-4.6	4.88	Stable	-1.4	-2.7	3.05	Stable

Table 5. The number of occurrences of points determined using Fredericton (Taşçı, 2003).

	Points	Periods								
		1 - 2			1 - 3			1 - 4		
		The number of occurrences			The number of occurrences			The number of occurrences		
		F (95%)	F (97.5%)	F (99%)	F (95%)	F (97.5%)	F (99%)	F (95%)	F (97.5%)	F (99%)
Reference points	1001	0	0	0	11	10	6	2	2	2
	1002	6	4	4	2	1	0	4	3	3
	1003	2	0	0	4	4	2	5	4	3
	1004	8	3	2	4	4	2	5	4	4
	1005	4	3	2	3	2	0	2	1	0
	1006	2	1	0	3	1	0	2	2	1
Object points	0003	4	4	2	7	6	5	9	8	5
	0005	0	0	0	3	2	1	4	3	2
	0007	4	3	3	6	5	3	6	6	2
	0009	4	3	0	3	2	1	9	6	5
	0011	3	3	2	2	1	0	10	6	5
	0013	4	4	2	2	2	1	9	9	7
	0015	2	1	1	3	2	1	1	0	0
	0017	2	1	1	6	4	3	5	5	3
	0019	7	6	4	8	8	4	6	5	4
	0021	0	0	0	2	1	0	2	1	0
	0023	2	2	1	1	1	1	4	2	0

Table 6. Stable and unstable points determined using Fredericton (Taşçı, 2003; Gökalp and Taşçı, 2009).

	Points	Periods 1 - 2	Periods 1 - 3	Periods 1 - 4
Reference points	1001	Stable	Unstable	Stable
	1002	Unstable	Stable	Stable
	1003	Stable	Stable	Unstable
	1004	Unstable	Stable	Unstable
	1005	Unstable	Stable	Stable
	1006	Stable	Stable	Stable
Object points	0003	Unstable	Unstable	Unstable
	0005	Stable	Stable	Stable
	0007	Unstable	Unstable	Unstable
	0009	Unstable	Stable	Unstable
	0011	Unstable	Stable	Unstable
	0013	Unstable	Stable	Unstable
	0015	Stable	Stable	Stable
	0017	Stable	Unstable	Unstable
	0019	Unstable	Unstable	Unstable
	0021	Stable	Stable	Stable
	0023	Stable	Stable	Stable

Table 7. Stable and unstable points determined by IWST, LAS, congruency test and Fredericton.

	Periods			Periods			Periods			Periods		
	1 - 2	1 - 3	1 - 4	1 - 2	1 - 3	1 - 4	1 - 2	1 - 3	1 - 4	1 - 2	1 - 3	1 - 4
	IWST			LAS			Congruency			Fredericton		
1001	Stable	Unstable	Stable	unstable	Unstable	Unstable	Stable	Unstable	Unstable	stable	Unstable	Stable
1002	Unstable	Unstable	Stable	unstable	Unstable	Stable	Stable	unstable	Stable	unstable	stable	Stable
1003	Stable	Stable	Stable	stable	Unstable	Stable	Stable	Stable	Stable	stable	Stable	Unstable
1004	Stable	Stable	Stable	stable	Stable	Stable	stable	Stable	Stable	unstable	Stable	Unstable
1005	Stable	Stable	Stable	stable	Stable	Stable	Stable	Stable	Stable	unstable	Stable	Stable
1006	Unstable	Unstable	Stable	unstable	Unstable	Stable	Unstable	Stable	Stable	stable	Stable	Stable
0003	Unstable	Unstable	Unstable	unstable	Unstable	Unstable	Unstable	Unstable	Unstable	unstable	Unstable	Unstable
0005	Stable	Stable	Stable	Stable	Unstable	Unstable	Stable	Stable	Unstable	stable	Stable	Stable
0007	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	unstable	Unstable	Unstable
0009	Stable	Stable	Unstable	Unstable	Stable	Unstable	Unstable	Stable	Unstable	unstable	Stable	Unstable

Table 7 Contd.

0011	Unstable	Stable	Unstable	Unstable	Unstable	Unstable	Unstable	Stable	Unstable	unstable	Stable	Unstable
0013	Unstable	Stable	Unstable	Unstable	Stable	Unstable	Unstable	Stable	Unstable	unstable	Stable	Unstable
0015	Stable	Unstable	Unstable	Stable	Unstable	Unstable	Stable	Unstable	Unstable	stable	stable	Stable
0017	Stable	Unstable	Stable	Stable	Unstable	Unstable	Stable	Unstable	Unstable	stable	Unstable	Unstable
0019	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	unstable	Unstable	Unstable
0021	Stable	Stable	Stable	Unstable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
0023	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

tation of the results.

When examining the displacement obtained by the IWST, LAS and Congruency method, the points with a displacement greater than or equal to 4 mm were accepted as unstable. This coincides with the horizontal accuracy of the observations that were calculated by MINQUE.

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