GeoScience Engineering

INVESTIGATION OF VERTICAL DEFORMATION AROUND TRABZON TIDE GAUGE STATION

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ABSTRACT

Nowadays, with the rapid development of technology, the importance of deformation measurement is increasing. Measuring the shape and position changes of natural or artificial structures as a result of external factors are called deformation measurements. In order to determine deformations, geodetic control networks are generally established and measurements are made at various periods in these networks. Deformation analysis is performed using the point coordinates obtained by evaluating the measurements made. GPS is generally used for horizontal and vertical directions and precision levelling method is generally used for vertical direction only in determining deformation in geodetic control networks. Measurements made in different periods are tested with deformation models and it is investigated whether there is deformation in the passing time. In this study, we aimed to examine the vertical crust movements in and around the tide gauge station in Trabzon harbour area. For this purpose, in a levelling network established in the study area, precision levelling measurements were made in two periods, June 2020 (1st period) and October 2020 (2nd period). The measured height differences were adjusted according to the free network method. In both periods, the t-distributed inconsistent test was applied and an inconsistent measure was found for a single route. Adjustment was made by removing the inconsistent measurements found. We investigated whether there has been any movement in the network between two periods by using the θ^2-criterion method, one of the static deformation model methods. The vertical movements that may occur between different periods have been determined and we investigated whether there is a vertical deformation around the tide gauge station. The calculations regarding the methods applied within the scope of the study were made using MATLAB program codes written by us.

Keywords: Adjustment; Deformation; Precise Levelling; Tide gauge; θ^2-Criteria Method

1 INTRODUCTION

The technical status of engineering structures should be monitored and estimated. For the purpose, researchers use various systems and measurement techniques [1]. Geodetic methods used to accurately determine the locations of the selected points for the monitored structure play an important role in monitoring buildings, bridges, and dams. Geodetic monitoring takes place using a variety of techniques and measurements. The most common are satellite navigation systems, photogrammetry and remote sensing, and laser scanning. However, classical geodetic control networks are still used for geodetic methods basically [2,3]. The structural deformations are based on the inscriptions of the positions (displacements) of the points in this network in the time. This kind of deformation can show by periodic measurements [4].

Many geodetic and non-geodetic methods are used to observe deformations. In geodetic methods, observing the deformations in the horizontal and vertical directions is based on the evaluation and analysis of the classical levelling or GPS measurements made periodically at the control points (networks) established for this purpose [5].

In Turkey, tide gauge stations are covered by Turkey National Sea Level Monitoring System (TUDES). Sea level and ancillary meteorological parameters are observed at each TUDES stations. Since tide gauge stations measure sea level relative to land upon which they are located, observed sea level signal contains true sea level and any possible vertical land movement signals (land subsidence or land uplift) [6].

The long-term sea level changes in coastal values have been followed by TUDES stations and these contribute to reference surface determination studies for Turkey's National Vertical Control Network (TUDK), geoid determination studies and height determination studies. The determination of the earth's crust movements that may occur in and around the tide gauge stations, which are of great importance in terms of scientific studies, are necessary studies for the accuracy and reliability of these studies.

The main causes of destructive and fatal earthquakes in the world are related to faults. The length of the faults can reach from several km to several thousand km. The lengths of the faults are directly proportional to the magnitude of the earthquakes. The length of a fault observed in shallow and large earthquakes reaches hundreds of km [7].

The Black Sea is located in the Anatolian region of the Alpine-Himalayan orogenic system, between the Eurasian plate in the north and the African-Arab plate in the south [8]. Although it is under the influence of a complex compressional tectonics controlled by the Alpine-Himalayan system today, opening tectonics has played a role in its formation. These compressional tectonic structures are expressed by the Balkanids in the west, the Pontides in the south, the Crimean highland mountains in the north and the Caucasus in the east [9].

2 METHOD

In this study, vertical movement of the earth's crust have been investigated in and around the tide gauge station in Trabzon, in the Eastern Black Sea Region, Turkey.

For this purpose, a levelling network has been established and measurements were made in different periods. The height differences between the points were determined with the precise levelling measurements made on the established levelling network. Then, free network adjustment was made in the levelling network with algorithms written in Matlab R2016b programming language. As a result of adjustment, the inverse weight matrix of the unknowns Q_{xx} and adjusted heights were obtained. These calculations have been made for two periods, June 2020 and October 2020. The quantities obtained from the result of adjustment in two periods were used in the θ^2-Criteria deformation analysis method, which is the static deformation model.

2.1 Precise Levelling Method

Precise levelling method is used in works requiring high precision, establishment of country levelling network, determining the deformations that may occur over time in engineering structures such as bridge, dam, harbour, tunnel, etc. that require very precise measurements. Mean error of precision levelling is $0.5mm/\sqrt{km}$. Since high precision is required, the tools used, the places where the points will be marked, measurement and calculation methods should be selected to ensure this precision [10].

In addition to these, in precision levelling measurements, in each foundation of the levelling, back-I, forward-I, forward-II, back-II are read in rods, so the height differences are measured twice. Precision levelling was done according to double run measure plan. In measurements, double run's difference does not exceed $\pm 4\sqrt{S}\ (mm)$ [11].

2.2 Free Adjustment of Geodetic Networks and Determination of Inconsistent Measures

Functional and stochastic models in free adjustment of levelling networks, respectively, are obtained as follows:

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$$v = Ax - l \tag{1}$$

$$P_i = \frac{1}{s_i(km)} \tag{2}$$

where v is corrections vector, A is coefficients matrix, l is observations vector, x is unknown vector, P_i is weight matrix, s_i is distance between points.

Normal equations can be determined by the least-squares method of Gauss in the Eq. (3):

$$A^T PA\, x = A^T P\, l \tag{3}$$

and unknown coefficients are obtained as follows:

$$x = (A^T PA)^{-1} A^T P\, l \tag{4}$$

where $(A^T P\, A) = N$ is normal equation coefficients matrix.

The exact values of the heights are obtained by adding the calculated adjustment unknowns (x) and the approximate values of the unknowns X_0 as Eq. (5):

$$X = X_0 + x \tag{5}$$

As a result of adjustment, the inverse weight matrix of the corrections and the variance of the unit measure, respectively, are calculated by Eq (6) and (7):

$$Q_{vv} = Q_{ll} - AQ_{xx}A^T \tag{6}$$

$$m_0^2 = \frac{v^T P\, v}{n-u+d} \tag{7}$$

where n is observation number, u is unknown number, d is datum parameter number.

Mean error of observation is as:

$$m_i = \mp \frac{m_0}{\sqrt{P_i}} \tag{8}$$

and mean error of unknowns is as:

$$m_{hi} = \mp m_0 * \sqrt{q_{xixi}} \tag{9}$$

where q_{xixi} is the i. diagonal element of Q_{xx}.

2.3 Determination of Inconsistent Observations

It is a common situation that geodetic measurements made for various purposes include gross error and inconsistent measurements. Gross errors in the measure group can be determined and removed while the correction equations of the adjusted model are established but it is not possible to determine the inconsistent measures that occur due to various reasons.

Inconsistent measurements containing errors of magnitude very close to random measurement errors can only be determined by the inconsistent measurement test applied in the result of adjustment calculation [12].

In Table 1, Baarda uses the theoretical variance (σ_0^2), Pope uses the estimated variance (s_0^2) found as a result of the adjustment, in the t test is used variance value (s_{0i}^2) calculated after the effect of this inconsistent measure is removed, instead of calculated with the inconsistent measure (s_0^2) [13].

Table 1. *Summary chart of inconsistent observation tests*

Method	Test Size	Distribution	Limit Value
Baarda	$T_{vi} = \lvert v_i \rvert / (\sigma_0 \sqrt{q_{v_i}})$	N(0.1) Normal Distribution	$N_{1-\alpha/2}$
Pope	$T_{vi} = \lvert v_i \rvert / (s_0 \sqrt{q_{v_i}})$	τ_f Tau Distribution	$\tau_{f,1-\alpha/2}$
t-test	$T_{vi} = \lvert v_i \rvert / (s_{0i} \sqrt{q_{v_i}})$	t_{f-1} t- Distribution	$t_{f-1,1-\alpha/2}$

2.4 Deformation Analysis by θ²-Criteria Method

With this method, in the deformation analysis, each period measure is freely adjusted separately, inconsistent observations are removed and the root mean squares errors (m_1 and m_2) of unit measure are calculated for each period [14].

The θ²-criteria method determines if there is any significant difference in coordinates in the points. It is determined whether there is important point movement between the two periods by calculating the balanced coordinate differences obtained from the periods.

Then, the difference vector (d) is shown:

$$d = x_2 - x_1 \tag{10}$$

The covariance matrix (Q_{dd}) of vector d is obtained as follows:

$$Q_{dd} = Q_{x1x1} + Q_{x2x2} = (A_1^T P_1 A_1)^+ + (A_2^T P_2 A_2)^+ \tag{11}$$

The θ²-criteria is computed as shown:

$$\theta^2 = d^T Q_{dd}^+ d \tag{12}$$

the rank (h) of Q_{dd} with assumption that there is no relation among two observation times are determined as follows:

$$h = rang(Q_{dd}) \tag{13}$$

Apriority variance (s_0^2) is determined from residuals' total squares obtained from the adjustments of the initial period (t1) and second period (t2) like below:

$$s_0^2 = \frac{v_1^T P_1 v_1 + v_2^T P_2 v_2}{f_1 + f_2} = \frac{f_1 s_{01}^2 + f_2 s_{02}^2}{f_1 + f_2} \tag{14}$$

where f_1 and f_2 are independence's degrees at the initial period (t1) and second period (t2). T is the statistical test value and it is computed as follows:

$$T = \frac{\theta^2}{s_0^2 h} = \frac{d^T Q_{dd}^+ d}{s_0^2 h} \tag{15}$$

The test value T is compared with the critical value F taken from table of F-distribution with (α) and the α is level of significance. If $T > F_{h,f,1-\alpha}$, then H_0 hypothesis is rejected. H_0 hypothesis is that: all points have remained constant. To determinate the deformation, the vector of difference may be divided into two pieces: if H_0 is valid, a

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constant piece F is showing control points and if H_0 is not valid, B piece is showing a moving piece. For this, *d* and Q_{dd} are properly segmented and vector of difference (dB) in moving group is as follows:

$$d = \begin{vmatrix} d_F \\ d_B \end{vmatrix} \tag{16}$$

$$Q_{dd} = \begin{vmatrix} Q_{FF} & Q_{FB} \\ Q_{BF} & Q_{BB} \end{vmatrix} \tag{17}$$

$$P_{dd} = Q_{dd}^{+} = \begin{vmatrix} P_{FF} & P_{FB} \\ P_{BF} & P_{BB} \end{vmatrix} \tag{18}$$

$$d_B = d_B - P_{BB}^{-1} P_{BF} d_F \tag{19}$$

$$P_{FF} = P_{FF} - P_{FB} P_{BB}^{-1} P_{BF} \tag{20}$$

where B index indicates moving points, F index indicates fixed points, P_{dd} weight matrix.

The θ^2-criteria value

$$\theta^2 = d^T Q_{dd}^{+} d = d_F^T P_{FF} d_F + d_B^T P_{BB} d_B \tag{21}$$

is divided into two independent components. $d_F^T P_{FF} d_F$ is discrepancy of point supposed to be fixed and $d_B^T P_{BB} d_B$ is discrepancy of each point supposed to be moved.

θ^2-criteria are calculated for each point at group B as follows:

$$(\theta_B^2)i = (d_B^T P_{BB} d_B)_i \quad , \quad i=1, 2,\dots n \tag{22}$$

here, *n* is the point's number. The deformation at the point is assumed to be maximum$(\theta_B^2)i$:

$$(\theta_B^2)max = max(\theta_B^2)_i \tag{23}$$

The point with the largest value $(\theta_B^2)max$ at group B is removed from the definition of datum, after the operation is returned by practicing the definition of new datum [15,16].

3 APPLICATION

The purpose of our research was to determine movements in TRBZ tide gauge station and its surroundings located in the Eastern Black Sea region, Trabzon province, and seaport.

3.1 Study Area

Trabzon seaport is located between latitudes 40°57'30" and 41°06'36" in the north and longitudes 40°02'30" and 39°25'00" in the east. Figure 1 shows Trabzon harbour and Figure 2 shows Trabzon tide gauge station.

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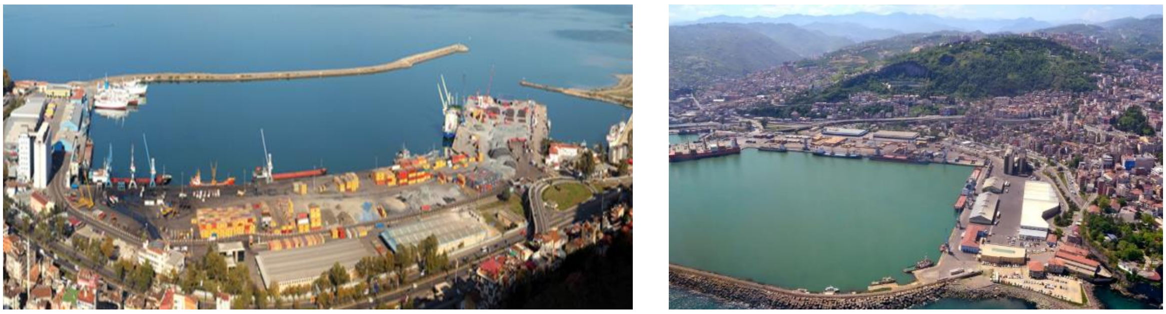

Figure 1. *Trabzon harbour*

Figure 2. *Trabzon tide gauge station*

3.2 Tectonic Structure of the Study Area

In terms of geographical location, Trabzon province is located in the Eastern Black Sea region. It is located in the North Zone of the Eastern Pontides with a length of approximately 500 km and a width of 200 km, extending along the east of the Black Sea coast [17].

Current geological, geophysical and GPS studies show that the active reverse fault and fold system in Georgia continues towards the Black Sea and active pressure deformation decreases from the Caucasus to the Black Sea. Active reverse faults belonging to the pressure deformation extend approximately 5–20 km from the coast of Trabzon and parallel to the coast. According to GPS data, the annual right lateral movement of the North Anatolian Fault is 24 mm/year, 3–5 mm/year in the Caucasus and 9 mm/year in the Eastern Anatolian Fault [18].

3.3 Establishment of the Levelling Network

A geodetic levelling control network was established in order to determine the vertical movements of earth crust around the Trabzon tide gauge station. This levelling network consists of the MAR-5 point in the tide gauge station, RS494/684 point on potter street number 1 and T1, T3, T4 and AN.N points, which are newly established with in the Trabzon seaport area. Elevation value of RS point (MAR-5) belonging to tide gauge station was obtained from General Directorate of Mapping. The height value of RS494/684 point was obtained from Trabzon Metropolitan Municipality. Levelling network points and Levelling network are shown in Figure 3 and Figure 4.

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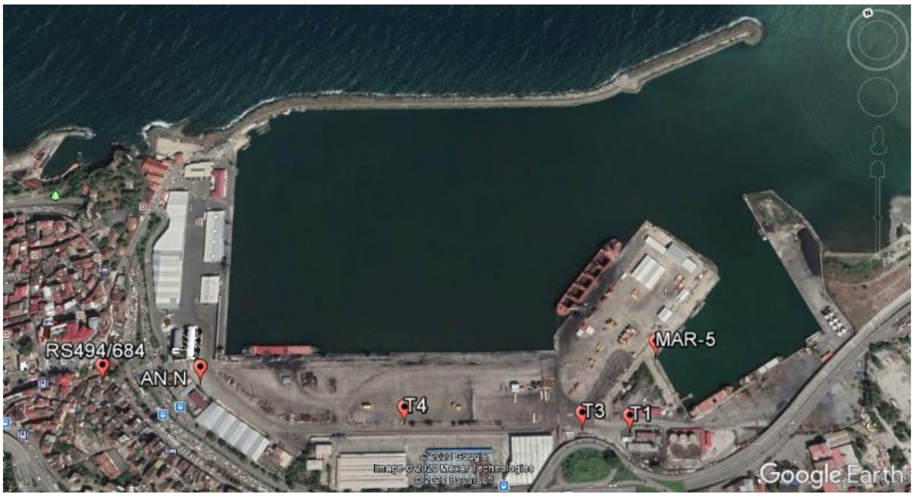

Figure 3. *Levelling network points*

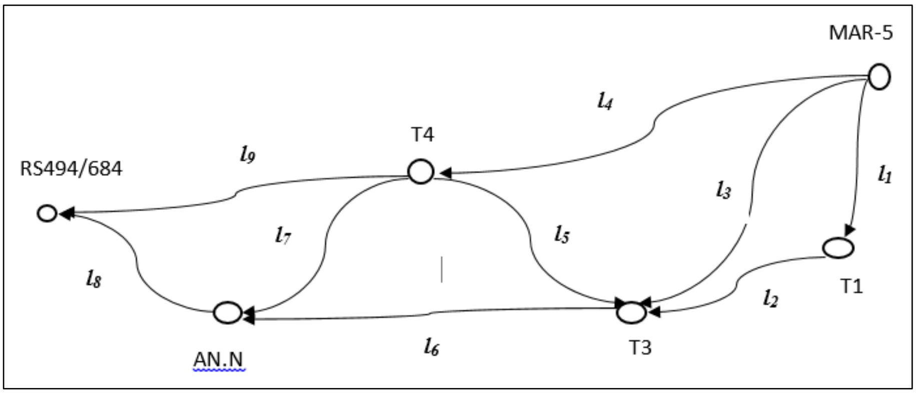

Figure 4. *Levelling network*

In the levelling network, precision levelling measurements were made in two periods: June 2020 (1st period) and October 2020 (2nd period). Precise levelling method was used on all routes as double run. While applying this method, attention was paid to the topographic structure of the land, weather conditions, the distance between the level and the rod should not exceed 30. In this way, we tried to obtain high precision measurements on all routes belonging to the network. Levelling was done with Electronic Digital Level.

3.4 Adjustment of Levelling Network Observations

The height differences measured in two periods are adjusted with the algorithms written by us in the MATLAB R2016b program according to the free adjustment of geodetic networks method. For free adjustment, the height differences ΔH_i of the points obtained from all the routes, the length of the routes $S_i(km)$ in kilometres and the approximate height values of the net points were used as input data in the program. In both periods, the t-distributed inconsistent measures test was applied and inconsistent measure was found for a single route in each period. Adjustment was continued by removing the inconsistent measurements found. Thus, the result of free net adjustment made with compatible measures, the adjusted heights of the net points (x_1, x_2) from Eq. (5), the sum of the squares of the corrections (v_1, v_2) and the inverse weight matrices of the unknowns (Q_{x1x1}, Q_{x2x2}) were calculated. In addition, from Eq. (9), the root mean square errors (mh) of the heights of the points in the network were calculated.

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3.5 Deformation Analysis in Levelling Net

The starting period of 9 June 2020 was accepted as (t_0) and 9 October 2020 was accepted as (t_1). The static deformation model determined deformations occurring between (t0) and (t1) times. The θ^2-criteria method of the static deformation methods was used. With the algorithms written by us in the MATLAB R2016b program, it was decided whether there was deformation in the network between (t_1) and (t_0) times.

Adjusted heights of the net points (x_1, x_2) obtained from the result of free net adjustment, sum of squares of corrections (v_1, v_2) and inverse weight matrices (Q_{x1x1}, Q_{x2x2}) were used as input data in the deformation analysis with the θ^2-criteria method. In the deformation analysis with the θ^2-criteria method, the θ^2-criteria from Eq. (12), the apriority mean error of the unit measure (s_0^2) from Eq. (14) and the test size (T) from Eq. (15) were calculated. By comparing the test size (T) with the F-table value (q), it was determined whether there was any deformation by performing a global test.

4 RESULTS AND DISCUSSION

The root mean square errors (m_h) of heights obtained from the 1st period measurements of the levelling points are shown in Table 2 and Figure 5.

Table 2. *Root mean square error of heights in period I.*

Points	Root mean square error of heights (mm)
MAR-5	1.30
T1	1.27
T3	1.10
T4	1.15
AN.N	1.82
RS494/684	2.77

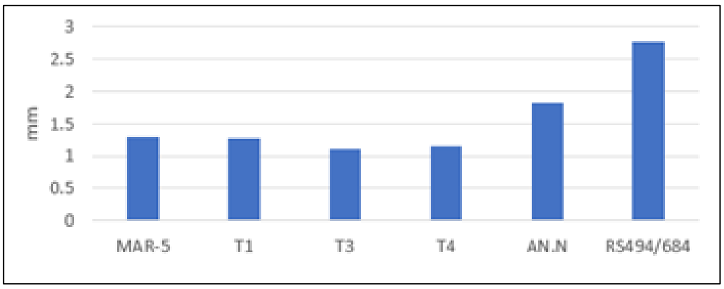

Figure 5. *Root mean square error of heights in period I.*

Table 2 and Figure 5 have shown that point RS494/684 has a maximum root mean squared with 2.77 mm.

The root mean square errors (m_h) of heights obtained from the second period measurements of the levelling points are shown Table 3 and Figure 6.

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Table 3. *Root mean square error of heights in Period II.*

Points	Root mean square error of heights (mm)
MAR-5	0.18
T1	0.18
T3	0.15
T4	0.18
AN.N	0.20
RS494/684	0.29

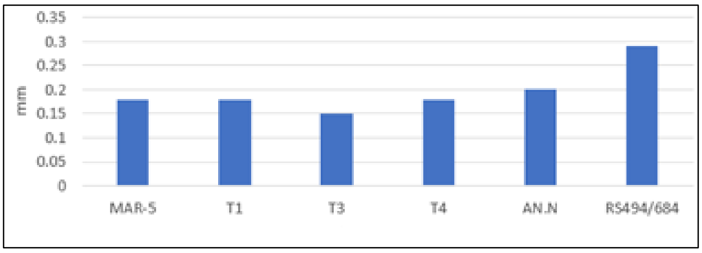

Figure 6. *Root mean square error of heights in Period II.*

Table 3 and Figure 6 have shown that point RS494/684 has a maximum root mean squared with 0.29 mm.

Deformation analysis values by θ^2- criteria method are shown in Table 4.

Table 4. *Deformation Analysis Values by θ^2- Criteria Method*

Tests	Results
θ^2- Criteria	0.0313
s_0^2	8.7430
Test Size (T)	$7.1513*10^{-4}$
F-Table (q)	4.3874
Decision	T<F No deformation

It is seen in Table 4 that according to the result of the deformation analysis with the θ^2-criterion method, the Test Size value (T) calculated between the periods (t_1) - (t_0) is smaller than F-Table value.

5 CONCLUSIONS

In this study, we examined the vertical crust movements in and around the tide gauge station in Trabzon harbour area in Eastern Black Sea region. For this purpose, a geodetic levelling control network has been established in the study area. In the levelling network established, precise levelling measurements were made in two periods, June 2020 (1st Period) and October 2020 (2nd Period). Precise levelling method was used on all routes as double run. The height differences measured in each period are adjusted according to the free network method in the program written by us in the MATLAB R2016b. The start period of 9 June 2020 (t_0) and 9 October 2020 (t_1) have been accepted. The deformations that occur between (t_0) and (t_1) times were determined by the static deformation model. θ^2- Criteria method was chosen among the static deformation methods and deformation analysis was performed in the program written by us in MATLAB R2016b program. The deformation analysis result is shown in Table 4.

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In the leveling network, according to the θ^2- Criteria method, the test size value (T) was calculated to be 7.1513 * 10^{-4} and the table value F was calculated as 4.3874. That is, it is seen that T test size value is smaller than F table value. This situation means that there is no deformation in the passing time in the levelling network.

This global test we carried out showed that there is no vertical significant movement in and around the Trabzon tide gauge station, which has been selected as the study area for a period of approximately 3 months.

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