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Estimation of strain accumulation of densification network in Northern Marmara Region, Turkey

I. Deniz[1] **and H. Ozener**[2]

[1]Istanbul Technical University, Department of Geomatics Engineering, Istanbul, Turkey
[2]Bogazici University, Kandilli Observatory and Earthquake Research Institute, Department of Geodesy, Istanbul, Turkey

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Abstract. Strain analysis is one of the methods for the kinematic analysis of the repeated geodetic measurements. In order to derive strain accumulation in Marmara Region, different institutions carried out several Global Positioning System (GPS) campaigns in 1999 and 2006. The GPS campaigns were performed on the geodetic network which cover the provinces: Kirklareli, Tekirdag, Bursa, Bilecik and Adapazari. Then, the displacements of the network stations were estimated by means of analysing the GPS space geodetic measurements. For the assessment of the datum differences between 1999 and 2006 on the station coordinates, 3-D Helmert transformation was applied to the coordinates of each 1999 and 2006 datum. Then, a global test was introduced to determine the significant deformation which occurred in the geodetic GPS network. Strain accumulation with a finite element model was then computed. First, triangles were constructed for the whole network with the Delaunay method. Hereafter, strain parameters were calculated for each triangle. Maximum values of strain accumulation were found around the surroundings of Marmara Ereglisi and Izmit, whereas minimum values are around Istanbul.

1 Introduction

After the Izmit and Duzce earthquakes (1999), renovations of Turkish National Fundamental GPS Network (TNFGN) and Turkish National Vertical Control Network (TNVCN) were done (TNFGN Report, 2001). Their station coordinates at the 2000.45 epoch were estimated. Densification networks tied to TNFGN and TNVCN were established by the institutions, i.e. Geodesy Department of Kandilli Observatory and Earthquake Research Institute of Bogazici University, Istanbul Metropolitan Municipality, General Command of Mapping (GCM), General Directorate of Land Registry and Cadastre, and the Scientific and Technical Research Council of Turkey (TUBITAK) – Marmara Research Center (MRC) in Kirklareli, Tekirdag, Bursa, Bilecik and Adapazari. Istanbul GPS Triangulation Network (IGTN) and Marmara Earthquake Region Land Information System (MERLIS) were formed covering this region (IGTN Report, 1999; MERLIS Report, 2006). To conclude, GPS campaigns were performed and analysed at different times by different institutions.

A test network was formed from a subset of the network stations of Turkish Continuously Operating Reference Stations (CORS-TR). Several GPS campaigns were performed on this network and analysed between 15 July and 30 October 2006 by three different companies namely TOPCON, TRIMBLE, and LEICA in order to test the performance of the GPS receivers (CORS-TR, 2006). Each company performed the measurements and evaluations using their own equipments.

This study aimed to compare the coordinate differences between the adjusted coordinates obtained from GPS observations in 1999 (converted to 2000.45 epochs) and the average of the adjusted coordinates obtained from the GPS observations by the aforementioned three companies in 2006 (converted to 2006.60 epochs) and to compute strain accumulation of the corresponding area by finite element model.

2 Test network and observations

Test network of CORS-TR was composed of 115 geodetic stations settled in Marmara Region which were chosen from the geodetic networks: TNFGN, MERLIS and IGTN. The datum of the so-called test network of CORS-TR was assigned by fixing the station coordinates of TNFGN to their a priori values at epoch 2000.45. Moreover, TNFGN network datum was constrained on International GNSS Service (IGS)

Correspondence to: H. Ozener
(ozener@boun.edu.tr)

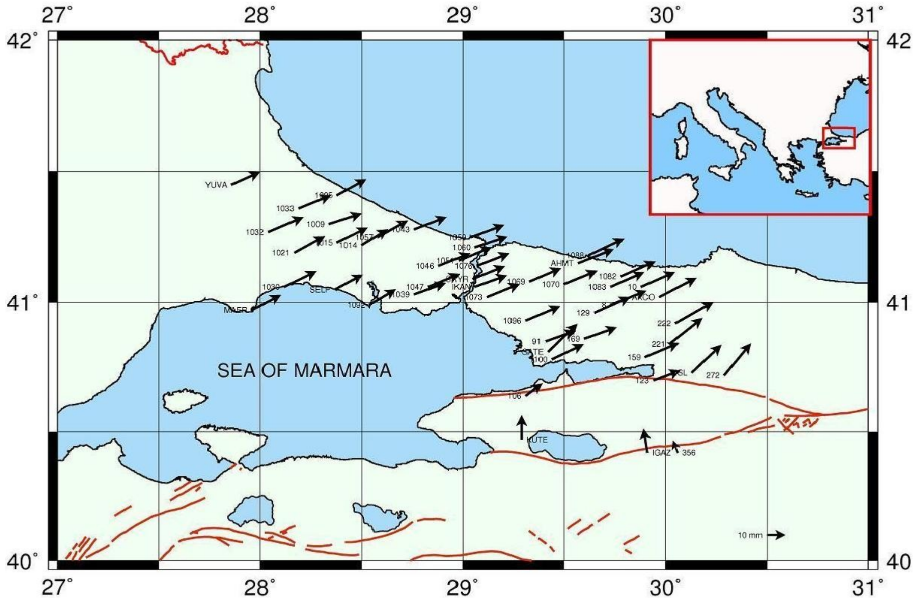

Fig. 1. The study area and the displacement vectors between ITRF96 solution at epoch 2000.45 and ITRF2000 solution at epoch 2006.60 on the test network of CORS-TR.

network ITRF96 coordinates of the IGS stations: ONSA, MADR, WTZR, MATE, ANKR, ZWEN, KIT3, NICO and BAHR. Another solution of the test network of CORS-TR GPS campaigns was carried out by fixing the IGS network defined in ITRF2000 at epoch 2006.60. In this case, test network of CORS-TR was fixed (a priori station coordinates were tightly constrained) to IGS network. The IGS stations, where coordinates are fixed to their a priori coordinates defined in ITRF2000 at epoch 2006.60, are namely ANKR, TUBI, DRAG, NOT1, SOFI, BUCU and MATE. Coordinates of the test network of CORS-TR stations estimated by two solutions have both different epochs and different datum. It is worth mentioning at this point that twelve ITRF realizations (solutions) have been successfully performed up to the present by International Earth Rotation and Reference Systems Service (IERS) including ITRF2008 which is the last release (Altamimi et al., 2007). The differences of transformation parameters of IERS, ITRF solutions are significant but too small in levels of magnitude, i.e. origin differences are in sub-centimetre level, rotation differences are in sub milli-arc-second level (mas) and scale differences are in part-per-billion level. The displacement vectors of the test network CORS-TR were calculated from the differences between the coordinates of ITRF96 datum (TNFGN datum) at epoch 2000.45 and ITRF2000 datum at epoch 2006.60. The displacement vectors between ITRF96 at epoch 2000.45 and ITRF2000 at epoch 2006.60 were shown in Fig. 1 and Table 1.

3 Investigation of datum

To examine the effect of two datums with different epochs on the displacement vectors, 3-D Helmert transformation parameters were estimated between the coordinates of ITRF96 at epoch 2000.45 and in ITRF2000 at epoch 2006.60. IGS stations of TNFGN were in ITRF96 datum (Table 2), whereas IGS stations of CORS-TR were in ITRF2000 datum (Table 3). To analyse the datum of two epochs, the 3-D Helmert transformation was applied to coordinates of ITRF96 and ITRF2000 of IGS stations which made up the datum of two epochs. The results of the Helmert transformation are the datum parameters between the two terrestrial reference frame (TRF) solutions of the test network of CORS-TR. Thus, computed transformation parameters (three translations, three rotations and a scale factor) between ITRF96 at epoch 2000.45 and ITRF2000 at epoch 2006.60 were compared with each other. Transformation parameters of each epoch were given in Table 4.

Transformation parameters of TNFGN datum (Table 4) indicates that the coordinates of ITRF96 at epoch 1997 of IGS stations which made up datum of TNFGN were consistent with the coordinates of ITRF2000 at epoch 1997. However, there was a significant translation between ITRF96 at epoch 1997 and ITRF2000 at epoch 1997 of IGS stations which made up datum of CORS-TR. It could be said that translations had an influence on the displacement vectors.

Two epochs had different number and distribution of datum points, so there were significant datum parameters between datum of TNFGN and CORS-TR. These differences occurred as a component of the deformation vector.

Table 1. Coordinates of stations and displacement vectors.

Station ID	ITRF96, at epoch 2000.45 coordinates		ITRF2000, at epoch 2006.60 coordinates		Local topocentric horizontal displacement (m)	
	UTM North (m)	UTM East (m)	UTM North (m)	UTM East (m)	North (m)	East (m)
AHMT	4558629.9657	716009.0616	4558630.0420	716009.2520	0.0763	0.1904
AKCO	4544921.0451	749831.6047	4544921.1511	749831.8056	0.1060	0.2009
GATE	4519935.3364	704228.1811	4519935.4903	704228.3381	0.1539	0.1570
IGAZ	4478642.2053	746550.2237	4478642.3342	746550.2037	0.1289	–0.0200
IKAN	4547867.4598	673391.4453	4547867.5220	673391.6180	0.0622	0.1727
KUTE	4482280.0875	693840.6258	4482280.2205	693840.6258	0.1330	0.0000
MAER	4535938.7897	580774.3147	4535938.8730	580774.4700	0.0833	0.1553
SELP	4545408.7113	614737.9823	4545408.7920	614738.1300	0.0807	0.1477
SISL	4513406.5434	764510.8057	4513406.6955	764510.9646	0.1521	0.1589
SRYR	4551063.7725	672248.2343	4551063.8430	672248.4070	0.0705	0.1727
YUVA	4589200.4569	571920.0501	4589200.5260	571920.2030	0.0691	0.1529
8	4542643.6284	729363.2981	4542643.7064	729363.4911	0.0780	0.1930
10	4551702.5224	741939.1269	4551702.6034	741939.3078	0.0810	0.1809
91	4526681.2330	703213.6371	4526681.2899	703213.7960	0.0569	0.1589
106	4502862.6652	695700.1477	4502862.7322	695700.2346	0.0670	0.0869
123	4511374.8130	748300.9752	4511374.8670	748301.1181	0.0540	0.1429
129	4539113.5760	723497.5294	4539113.6620	723497.7203	0.0860	0.1909
159	4521174.5075	745140.2310	4521174.5845	745140.4119	0.0770	0.1809
169	4527929.1286	719270.4019	4527929.1906	719270.5758	0.0620	0.1739
221	4525838.1926	754937.8958	4525838.3351	754938.0743	0.1425	0.1785
222	4534247.0760	756584.6923	4534247.1932	756584.8957	0.1172	0.2034
272	4513335.9567	778244.4418	4513336.1309	778244.5852	0.1742	0.1434
356	4478839.4843	759791.7704	4478839.5449	759791.7472	0.0606	–0.0232
1009	4573042.9155	611960.8810	4573042.9730	611961.0570	0.0575	0.1760
1014	4564348.4665	625422.7841	4564348.5530	625422.9240	0.0865	0.1399
1015	4564919.1198	615900.1765	4564919.2020	615900.3420	0.0822	0.1655
1021	4560644.1557	598502.3869	4560644.2460	598502.5500	0.0903	0.1631
1025	4585338.9555	615468.9838	4585339.0430	615469.1410	0.0875	0.1572
1030	4546449.0771	594320.3187	4546449.1630	594320.4920	0.0859	0.1733
1032	4568711.7575	586879.3524	4568711.8390	586879.5420	0.0815	0.1896
1033	4579699.9469	599700.7572	4579700.0180	599700.9300	0.0711	0.1728
1039	4543623.0522	647782.5407	4543623.1140	647782.7090	0.0618	0.1683
1043	4571522.6329	647169.1242	4571522.7000	647169.2980	0.0671	0.1738
1046	4555861.4332	657506.8844	4555861.5010	657507.0530	0.0678	0.1686
1047	4547418.1158	654015.5479	4547418.1860	654015.7160	0.0702	0.1681
1051	4558793.4240	666527.9618	4558793.4960	666528.1350	0.0720	0.1732
1057	4567889.1230	632774.3269	4567889.2150	632774.4900	0.0920	0.1631
1059	4569025.5329	670922.1698	4569025.6000	670922.3480	0.0671	0.1782
1060	4563780.8334	673054.6312	4563780.8920	673054.8050	0.0586	0.1738
1069	4550626.4246	695392.2452	4550626.4980	695392.4140	0.0734	0.1688
1070	4549821.1872	709655.4251	4549821.2610	709655.6040	0.0738	0.1789
1073	4542814.0288	678310.6545	4542814.1000	678310.8280	0.0712	0.1735
1076	4556505.8328	674024.7009	4556505.9010	674024.8740	0.0682	0.1731
1082	4554060.6932	733417.8868	4554060.7750	733418.0710	0.0818	0.1842
1083	4549251.4406	729395.9647	4549251.5210	729396.1440	0.0804	0.1793
1088	4561844.8930	720079.7593	4561844.9850	720079.9510	0.0920	0.1917
1092	4538650.6465	629486.5908	4538650.7320	629486.7330	0.0855	0.1422
1096	4533201.1617	694514.8406	4533201.2410	694515.0260	0.0793	0.1854
1100	4517398.0544	705998.5364	4517398.1370	705998.7060	0.0826	0.1696

Table 2. Coordinates of IGS Stations of TNFGN.

Station ID	ITRF96 Coordinates at Epoch 1997.0		
	X (m)	Y (m)	Z (m)
ANKR	4121948.602	2652187.958	4069023.671
WTZR	4075580.697	931853.669	4801568.044
MATE	4641949.718	1393045.282	4133287.333
ONSA	3370658.674	711877.032	5349786.866
KIT3	1944945.365	4556652.206	4004325.969
ZWEN	2886325.555	2155998.407	5245816.135
NICO	4359415.854	2874116.991	3650777.707
BAHR	3633909.068	4425275.486	2799861.265

Table 3. Coordinates of IGS Stations of CORS-TR (CORS-TR Report, 2006).

Station ID	ITRF2000 Coordinates at Epoch 1997.0		
	X (m)	Y (m)	Z (m)
ANKR	4121948.524	2652187.904	4069023.758
TUBI	4211317.316	2377865.929	4144663.268
DRAG	4432980.620	3149432.112	3322110.468
NOT1	4934546.203	1321265.036	3806456.124
SOFI	4319372.078	1868687.819	4292063.947
BUCU	4093760.836	2007793.835	4445129.965
MATE	4641949.526	1393045.455	4133287.465

4 Determination of strain accumulation

4.1 Determination of strain in a network with the global test

In this study, to analyse significant deformation between two epochs and strain parameters in 3-D, a global test was applied to the network. Free network adjustment was introduced for each campaign. For the global test, the differences of 3-D coordinates of two epochs were used. These differences (Fig. 1) were taken as the vector of deformations (Brunner, 1979).

The general equation of the vector of deformations can be written as;

$$d = Bu \, , \tag{1}$$

where **B** is the matrix of coefficients for one common station, $\boldsymbol{u}$ is the vector of unknown parameters (translations t, extensions ε, shearing strain γ and rotations ω).

$$\mathbf{B} = \begin{vmatrix} 1 & 0 & 0 & x & 0 & 0 & y & z & 0 & 0 & z & -y \\ 0 & 1 & 0 & 0 & y & 0 & x & 0 & z & -z & 0 & x \\ 0 & 0 & 1 & 0 & 0 & z & 0 & x & y & y & -x & 0 \end{vmatrix} , \tag{2}$$

$$\boldsymbol{u} = \left(\mathbf{B}^T \mathbf{B}\right)^{-1} \mathbf{B}^T d \, , \tag{3}$$

where d is the coordinate differences.

Root mean square error of the a posteriori unit weight is calculated by

$$m_0 = \pm \sqrt{\frac{\boldsymbol{v}^T \boldsymbol{v}}{n-u}} = \pm 0.02324$$

where $\boldsymbol{v}$ is the coordinate residual vector, n is the number of coordinates included in the global test, u donates to the number of unknowns. Below the parameter vector $\boldsymbol{u}$ is shown with their corresponding precisions.

$$\boldsymbol{u} = \begin{vmatrix} t_x \\ t_y \\ t_z \\ \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \frac{1}{2}\gamma_{12} \\ \frac{1}{2}\gamma_{23} \\ \frac{1}{2}\gamma_{13} \\ \omega_{11} \\ \omega_{22} \\ \omega_{33} \end{vmatrix} = \begin{vmatrix} -0.12540 \pm 0.00413 \\ 0.13045 \pm 0.00522 \\ 0.05817 \pm 0.00351 \\ 0.00085 \pm 0.00075 \\ 0.00136 \pm 0.00070 \\ -0.00038 \pm 0.00024 \\ 0.00095 \pm 0.00073 \\ -0.00012 \pm 0.00040 \\ 0.00207 \pm 0.00064 \\ -0.00203 \pm 0.00063 \\ -0.00011 \pm 0.00034 \\ 0,00080 \pm 0.00061 \end{vmatrix}_{\mathrm{ITRF96}} \qquad t \cdot m_u = \begin{vmatrix} 0.006848 \\ 0.008655 \\ 0.005820 \\ 0.001244 \\ 0.001167 \\ 0.000401 \\ 0.001204 \\ 0.000663 \\ 0.001066 \\ 0.001048 \\ 0.000567 \\ 0.001011 \end{vmatrix}$$

t-test at 95% confidence interval was applied with $f = 135$ (degrees of freedom) and $\alpha = 0.05$ (significance level) to the results. Then, t-test critical value became $t_{0.95} = 1.658$.

The results revealed that there were significant translations (t_x, t_y, t_z), strain accumulation (ε_{22}) in the network. There was also a significant rotation around $x(\omega_{11})$ and a shearing strain (γ_{13}). Values of strain accumulation (ε_{11}), rotation around z-axis (ω_{33}) and shearing strain (γ_{12}) were close to being statistically significant. These results show that there are deformations in the directions of x, y and z axis.

4.2 Determination of strain accumulation by finite element model

As seen in Sect. 4.1, there were significant translations and rotations in the network. Therefore, the selection of an independent way of determining strain accumulation from datum parameters should be done. The ratio of baselines is independent from datum. Consequently, a model of calculating strain parameters with ratio of baselines, which is called finite element model, was used in this study.

Least square adjustment is applied to observations at two epochs separately. Linear extension of a baseline in a network become

$$\varepsilon = \frac{S' - S}{\Delta t \cdot S} \, , \tag{4}$$

where S is the baseline at epoch (t_1), S' is the baseline length at epoch (t_2), Δt is the time interval ($t_2 - t_1$) between two epochs.

If the time interval between two epochs, Δt is known, strain rate ε can be derived. However, if Δt is not taken into account, ε will become strain accumulation.

Table 4. Transformation parameters of epoch 2000.45 and 2006.60.

	TNFGN	CORS-TR
Scale	1.+0.001 ppm ± 0.0006 ppm	1.+0.19 ppm ± 0.027 ppm
Rotation about X axis	–0.00046″ ± 0.00014″	–0.011″ ± 0.013″
Rotation about Y axis	0.00027″ ± 0.00021″	0.001″ ± 0.029″
Rotation about Z axis	–0.00003″ ± 0.00015″	–0.004″ ± 0.006″
Translation along X axis	0.015 ± 0.006 m	–0.639 ± 0.613 m
Translation along Y axis	0.019 ± 0.004 m	–0.322 ± 0.255 m
Translation along Z axis	–0.022 ± 0.005 m	–1.008 ± 0.725 m

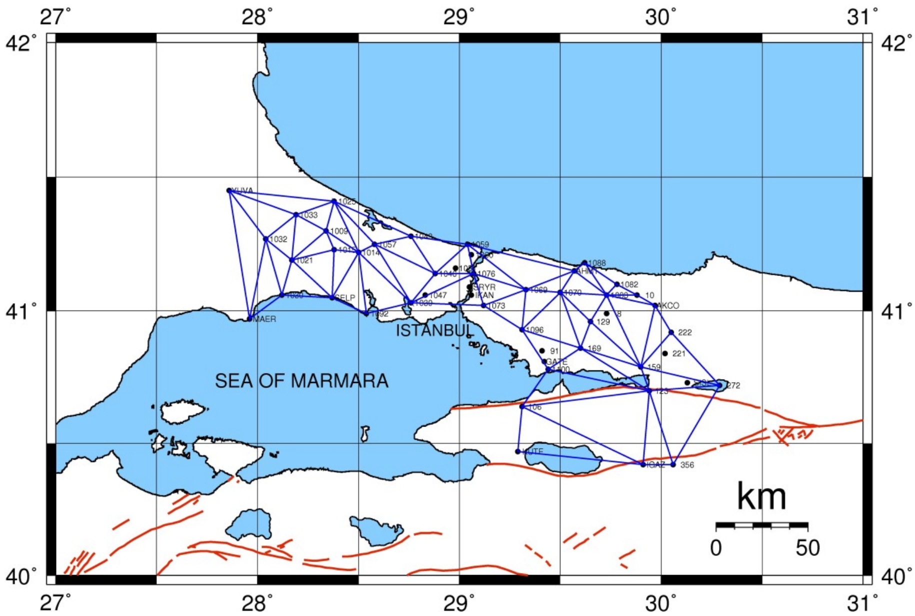

Fig. 2. Triangulation of the network.

Linear extension of the baseline which has t azimuth is,

$$\varepsilon = e_{xx}\cos^2 t + e_{xy}\sin 2t + e_{yy}\sin^2 t \,. \tag{5}$$

where e_{xx}, e_{xy} and e_{yy} are the strain tensor parameters. In order to calculate parameters of strain tensor, the general equation written above is used. The network has to be constructed of triangles. Then strain tensor has to be calculated for each triangle in the network. Three general equations are created for each baseline of a triangle. In this study, triangles for the network were constructed by using the Delaunay triangulation method. In the case of the intersection of the fault and baseline of a triangle, linear extension of the baseline was the sum of the translation component and strain component. Error strain could be obtained from the results in this situation. Therefore, triangles were simplified and designed not to intersect with the fault (Fig. 2).

Thus, e_{xx}, e_{xy}, e_{yy} for each triangle are found for time interval between 2000.45 and 2006.60 epochs. These parameters of strain tensor are the strain parameters of the point of equilibration of each triangle (Salmon, 1931; Denli, 1998). Subsequently, strain parameters shown below could be calculated from the parameters of strain tensor (Salmon, 1931; Deniz, 1997).

$$\Delta = e_{xx} + e_{yy} \,, \tag{6}$$

$$\gamma_1 = e_{xx} - e_{yy} \,, \tag{7}$$

$$\gamma_2 = 2e_{xy} \,, \tag{8}$$

$$\gamma = \sqrt{\gamma_1^2 + \gamma_2^2} \,, \tag{9}$$

where Δ is dilatancy, γ_1 is principal shear strain, γ_2 is engineering shear strain and γ is total shear strain.

Principal strain parameters are calculated by the following equations.

$$E_1 = \frac{1}{2}(\Delta + \gamma) \,, \tag{10}$$

$$E_2 = \frac{1}{2}(\Delta - \gamma) \,, \tag{11}$$

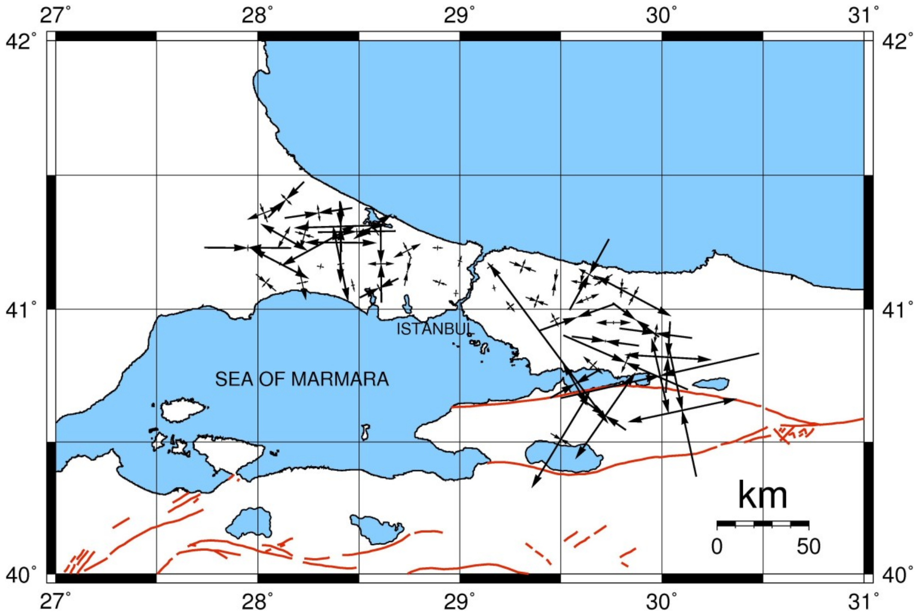

Fig. 3. Principal strain parameters of the network.

$$\beta = \arctan\left(\frac{e_{xy}}{E_1 - e_{xy}}\right), \quad (12)$$

where E_1 is maximum principal strain, E_2 is minimum principal strain and β is direction of maximum principal strain arc.

Equations of maximum shear strain E_{SHEAR} and maximum normal strain E_{INTER} are given below.

$$E_{SHEAR} = 0.5(E_1 - E_2), \quad (13)$$

$$E_{INTER} = 0.5(E_1 + E_2). \quad (14)$$

The process for computing precisions of calculated strain parameters by finite element model is

$$C_{xx} = \begin{bmatrix} m_x^2 & 0 \\ 0 & m_y^2 \end{bmatrix} = \begin{bmatrix} (1.5\ \text{cm})^2 & 0 \\ 0 & (1.5\ \text{cm})^2 \end{bmatrix}$$

where C_{xx} denotes the covariance matrix of the adjusted coordinates of TNFGN, IGTN and MERLIS networks.

Mathematical relation between the cofactor matrix is $Q_{\Delta S \Delta S} = 4Q_{xx}$, it becomes;

$$C_{\Delta S \Delta S} = 4\begin{bmatrix} m_x^2 & 0 \\ 0 & m_y^2 \end{bmatrix} = 4\begin{bmatrix} (1.5\ \text{cm})^2 & 0 \\ 0 & (1.5\ \text{cm})^2 \end{bmatrix},$$

and root mean square error of the differences of baselines between two epochs are derived as;

$$m_{\Delta S \Delta S} = \pm 4.24\ \text{cm}.$$

If the average baseline of test network is taken as 25 km, expected error ratios of strain parameters is

$$m_{\varepsilon} = \frac{m_{\Delta S \Delta S}}{S_{av}} = \pm 1.7\ \text{ppm}.$$

Principal strain parameters were calculated for the network by a finite element model using a programme coded in FORTRAN language (Deniz, 2007). The differences between the coordinates of 2000.45 and 2006.60 epochs were used for the calculations. Principal strain parameters of each triangle were given in Fig. 3 and Table 5.

Equilibration points, which have close strain parameter values, were gathered into groups in order to simplify the interpretations of the result. Principal strain parameters of each group were shown in Fig. 4.

5 Results and discussion

Displacement vectors (Fig. 1) indicates that there were significant displacements within 6.5 cm and 22.8 cm between the 2000.45 and 2006.60 epochs.

The results of Helmert transformation (Table 4) revealed that there was a significant translation in the datum of CORS-TR.

Choosing the model of calculating strain parameters should be done with respect to the state of the datum of networks. Strain parameters should be calculated from geodetic data which were independent from datum parameters. Finite element model that relied on the deformations of network baselines, which is the most suitable model for the calculation of strain parameters, was used in this study.

Firstly, for this method triangles were formed with Delaunay triangulation method. Triangles which are intersected with the fault were redesigned in order to minimize the errors. Then, strain parameter of equilibration of each triangle was calculated.

Table 5. Principal strain parameters computed for each triangle in the network.

Triangle Corner Points	Coordinates of Point of Equilibration		Principal Strain Components		Angle of the Principal Strain β (grad)	E_{INTER} (µs)	E_{SHEAR} (µs)
	North (m)	East (m)	E_1 (µs)	E_2 (µs)			
YUVA,MAER,1032	4564617.001	579857.906	0.25	–3.18	–0.40	–1.46	1.72
MAER,1032,1030	4550366.541	587324.662	0.45	–0.95	–44.81	–0.25	0.70
1032,1030,1021	4558601.663	593234.019	2.37	–0.13	69.52	1.12	1.25
YUVA,1032,1033	4579204.054	586166.72	1.33	–0.73	–76.22	0.30	1.03
1032,1033,1021	4569685.287	595027.499	1.97	0.89	66.87	1.43	0.54
1033,1021,1009	4571129.006	603388.008	1.10	–0.71	–17.26	0.19	0.91
YUVA,1033,1025	4584746.453	595696.597	0.57	–1.84	49.63	–0.63	1.21
1033,1025,1009	4579360.606	609043.541	0.61	–2.51	9.28	–0.95	1.56
1025,1009,1014	4574243.446	617617.55	3.41	–1.86	–98.06	0.78	2.64
1030,SELP,1021	4550833.981	602520.229	1.32	–0.43	13.99	0.45	0.87
SELP,1021,1015	4556990.662	609713.515	0.22	–0.24	–11.56	–0.01	0.23
1021,1009,1015	4566202.064	608787.815	3.10	–0.02	–68.16	1.54	1.56
1009,1015,1014	4567436.834	617761.281	2.97	2.63	–0.52	2.80	0.17
1015,1014,SELP	4558225.433	618686.981	2.83	–0.25	12.67	1.29	1.54
SELP,1092,1014	4549469.275	623215.786	0.47	–0.12	15.62	0.17	0.29
1092,1014,1039	4548874.055	634230.639	0.34	–1.57	29.92	–0.62	0.96
1025,1014,1057	4572525.515	624555.365	0.28	–2.85	0.85	–1.29	1.57
1014,1057,1039	4558620.214	635326.551	–0.97	–2.85	–99.51	–1.91	0.94
1057,1039,1046	4555791.203	646021.251	–0.05	–1.03	87.41	–0.54	0.49
1025,1057,1043	4574916.904	631804.145	1.69	–0.77	–63.24	0.46	1.23
1057,1043,1046	4565091.063	645816.779	1.11	–0.65	–69.88	0.23	0.88
1043,1046,1059	4565469.866	658532.726	0.19	–0.37	–4.09	–0.09	0.28
1059,1046,1076	4560464.266	667484.585	0.21	–0.39	81.74	–0.09	0.30
1046,1076,1039	4551996.773	659771.375	–0.24	–0.52	–21.47	–0.38	0.14
1076,1039,1073	4547647.638	666705.965	0.20	–0.24	97.69	–0.02	0.22
1059,1076,1069	4558719.263	680113.039	0.37	–0.25	37.92	0.06	0.31
1076,1069,1073	4549982.095	682575.867	0.25	0.13	12.83	0.19	0.06
1069,1073,1096	4542213.872	689405.913	0.52	–0.33	43.61	0.09	0.42
1059,1069,AHMT	4559427.308	694107.826	0.56	–1.02	–22.71	–0.23	0.79
1069,AHMT,1070	4553025.859	707018.911	–0.03	–0.98	91.19	–0.50	0.47
AHMT,1070,1083	4552567.531	718353.484	0.75	–0.85	89.48	–0.05	0.80
1069,1096,1070	4544549.591	699854.170	0.54	–0.85	–21.56	–0.16	0.70
1096,1070,169	4536983.826	707813.556	0.57	–0.37	30.29	0.10	0.47
1070,169,129	4538954.631	717474.452	–0.04	–2.94	21.70	–1.49	1.45
AHMT,1088,1083	4556575.433	721828.262	0.87	–2.96	67.99	–1.05	1.92
1088,1083,1082	4555052.342	727631.204	0.10	–0.75	34.52	–0.32	0.43
1083,1082,10	4551671.552	734917.659	0.47	–0.68	94.74	–0.11	0.57
10,AKCO,1083	4548625.003	740388.899	3.14	–0.76	68.77	1.19	1.95
AKCO,1083,159	4538448.998	741455.933	–0.02	–2.10	–40.57	–1.06	1.04
1083,159,129	4536513.175	732677.908	1.28	–0.12	–99.59	0.58	0.70
129,159,169	4529405.737	729302.721	0.12	–2.48	–8.62	–1.18	1.30
159,169,123	4520159.483	737570.536	0.81	–4.98	–26.17	–2.08	2.90
169,123,1100	4518900.665	724523.305	0.96	0.46	53.04	0.71	0.25
AKCO,222,159	4533447.543	750518.843	0.70	–2.68	–8.25	–0.99	1.69
222,159,SISL	4522942.709	755411.91	3.18	–2.61	96.29	0.28	2.90
159,SISL,123	4515318.621	752650.671	2.81	–7.43	14.12	–2.31	5.12
1096,169,1100	4526176.115	706594.593	0.85	0.29	92.14	0.57	0.28
KUTE,106,IGAZ	4487928.319	712030.332	4.14	–0.87	–34.53	1.63	2.50
1070,1083,129	4546062.068	720849.64	0.92	–0.17	–74.74	0.37	0.55
272,356,123	4501183.418	762112.396	4.09	–4.97	–86.56	–0.44	4.53
123,IGAZ,106	4497626.561	730183.782	3.86	–1.83	–38.58	1.02	2.85
1100,123,106	4510545.178	716666.553	1.84	–2.10	33.36	–0.79	2.62

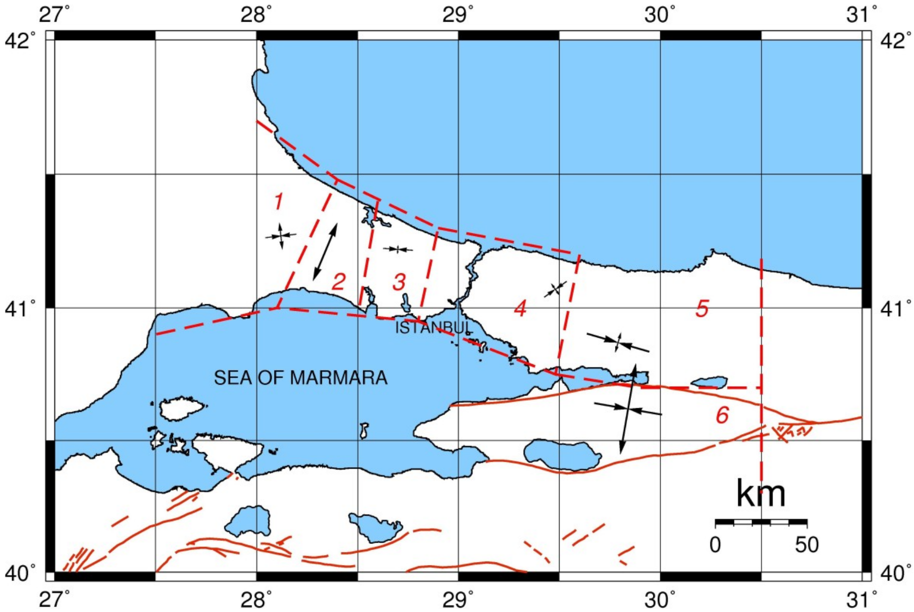

Fig. 4. Principal strain parameters of each group.

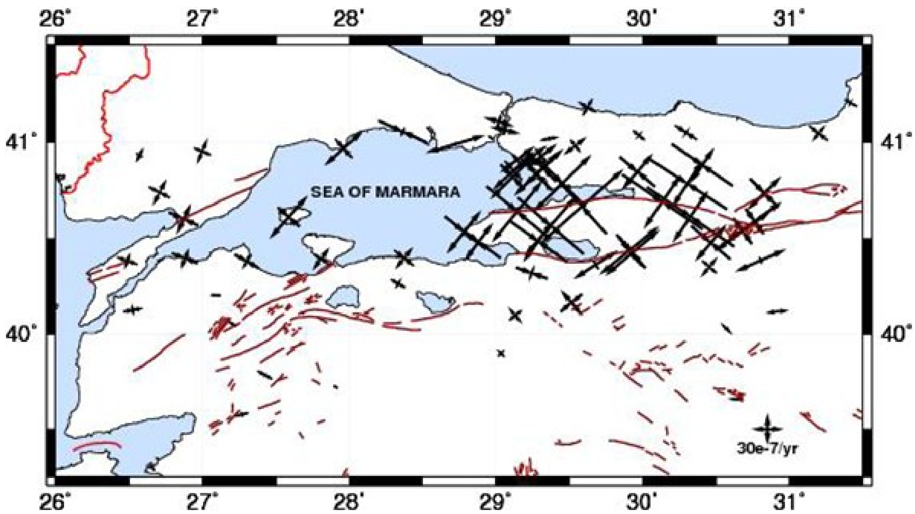

Fig. 5. Principal strain rates from the study of Ozener et al. (2009).

Majority of strain parameters of the network obtained from the three dimensional differences were significant. The results of the global test indicated that there was a significant deformation in the network.

Baseline ratios, which were computed for baselines of triangles, were compared with $m\varepsilon = \pm 1.7$ cm which was calculated in Sect. 4.2. The majority of ratios were larger than 2 ppm. Therefore, this indicates that calculated strain parameters were significant.

Strain parameters in Table 5 shows that maximum values of strain accumulation were around Marmara Ereglisi and Izmit, while minimum values were around Istanbul.

Although the covered regions by this study and Ozener et al. (2009) do not fully match, they have four stations (AKCO, IGAZ, KUTE and SELP) in common. As well as the directions and signs (compression or extension) of strain parameters of this study are consistent with the results of the study of Ozener et al. (Fig. 5), the scalar values of strain parameters are computed as smaller. This result has been expected since deformation pattern naturally changes over time and besides GPS data span and locations of station points differ from each other in both studies.

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