

DETERMINATION OF CRUSTAL MOVEMENTS IN MARMARA REGION USING GPS BASELINES FROM PRE AND POST İZMİT EARTHQUAKE (17 AUGUST 1999)

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İZMİT DEPREMİ (17 AĞUSTOS 1999) ÖNCESİ VE SONRASI GPS ÖLÇÜLERİNİ KULLANARAK MARMARA BÖLGESİNDE YERKABUĞU HAREKETLERİNİN BELİRLENMESİ

ÖZET

17 Ağustos 1999 İzmit depremi, Marmara Bölgesinin doğu kesiminde yer kabuğunu önemli derecede deformasyona uğratmış ve Kuzey Anadolu Fay kuşağının kuzey kolu boyunca yaklaşık 150-km uzunluğundaki bir bölümünü kırmıştır. Bu çalışmanın amacı bu bölgede 17 Ağustos 1999 İzmit depreminin öncesi ve sonrasında gerçekleştirilen GPS ölçülerini kullanarak yer kabuğu hareketlerini belirlemektir. Bölgede oluşturulmuş bir gözlem ağından elde edilmiş veriler için yapılan analizler sonucunda deprem öncesi ve deprem sonrası periyotlar arasında en büyük yatay konum değişimi yaklaşık 1.73 m ile bu ağın GLCK noktasında bulunmuştur. Ayrıca, GPS bazlarında anlamlı deprem sonrası değişimler gözlenmiş ve deprem sonrası periyotlar arasında, yaklaşık 1-2 cm'lik baz farkları belirlenmiştir.

ABSTRACT

17 August 1999 İzmit earthquake significantly deformed the earth's crust in the eastern Marmara region and broke a about 150-km long segment of the northern branch of North Anatolian Fault zone. The purpose of this paper is to determine crustal movements using GPS data observed for a geodetic network pre and post the earthquake in this area. A large displacement of about 1.73 m in the horizontal component between pre and post earthquake epochs was found at GLCK site of the network. Significant post-seismic deformations were also observed in GPS positions. Additionally, baseline differences of about 1-2 cm was determined between post earthquake epochs.

1. INTRODUCTION

The Marmara region is an active tectonic zone characterized by the transition between the dextral strike-slip regimes of the North Anatolian Fault (NAF) that is the boundary between the Anatolian and the Eurasian plates (Figure 1). This region is deforming along the branches of NAF. The 17 August 1999 İzmit earthquake occurred in the eastern Marmara region along the NAF zone and broke a 150-km long segment of the northern branch of the NAF. The epicenter of the August 17th earthquake was located at 40.76° N latitude and 29.97° E longitude. The earthquake had a depth of around 10 km and lasted 45 seconds [3]. The earthquake's magnitude (M_w) was observed 7.5 [15].

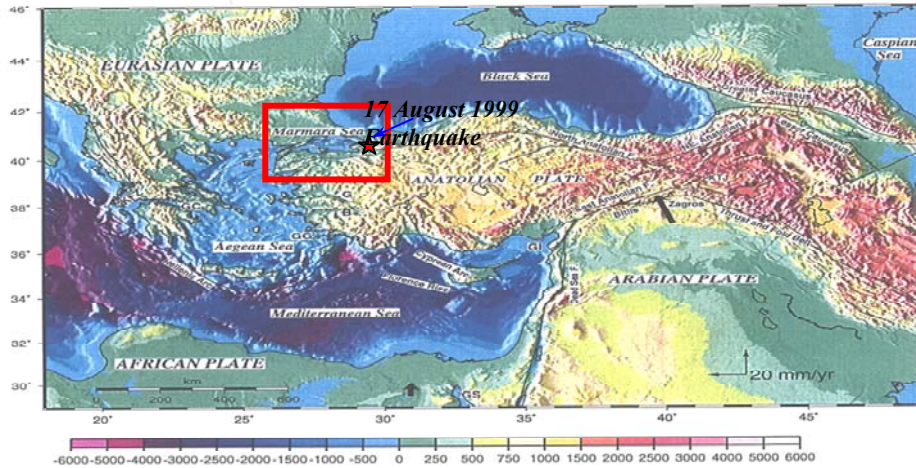


Figure 1. Tectonic map of the eastern Mediterranean region superimposed on topography and bathymetry [9]

The Crustal movements and tectonic plate motions in this region have been monitored to identify the seismic risk using GPS positions from various studies before and after the earthquake [2, 6, 7, 8, 9, 11, 13]. Straub et al. [13] estimated total fault-crossing slip rate relative to İstanbul (located at 41.1° N, 29.02° E) of about 20 ± 3 mm/yr using GPS observations in the Marmara region [9]. Ayhan et al. [1] computed the NAF slip rates as 25 mm/yr and 24 ± 1 mm/yr from the GPS velocities and Ayhan et al. [2] also computed the NAF slip rates that vary between 11 and 26 mm/yr in this region.

After 17 August İzmit Earthquake, Reilinger et al. [12] computed linear post-seismic displacements rates in a weighted Least-Squares procedure using the station coordinates of 75-day solutions and their covariance. Ergintav et al. [7] showed, however, the temporal and spatial post-seismic deformation rates, computed on the basis of GPS results for the first 298 days following the 17 August 1999 İzmit earthquake using time dependent relaxation function for each station.

In this paper, the GPS data collected for a geodetic network in the Marmara region pre and post the earthquake were studied. The aim of the study is to determine crustal deformations of this area using GPS data observed pre and post the earthquake in this area.

2. GPS MEASUREMENTS

The GPS baselines components between GPS sites and their covariance matrices in the previous studies were used [7, 10] whose authors estimated them using data from a Marmara Continuous GPS Network (MAGNET) [7, 15]. The GPS data have been analyzed, following the standard procedures using the GAMIT GPS processing software as described in Mc Clusky et al. [10]. We also studied four GPS epochs carried out before and after the 17 August 1999 İzmit earthquake to determine crustal deformation fields (Table I).

Table 1. GPS sites and time intervals of the epochs

Sites	Latitude ^a	Longitude ^a	H (m)	I ^{b1} 1998.77 ^c	II ^{b1} 1999.40 ^c	III ^{b2} 2000.25 ^c	IV ^{b2} 2000.64 ^c
BADA	40° 51' 07"	29° 07' 32"	37.623	*	*	*	*
CINA	40° 38' 22"	29° 08' 35"	169.891	*	*	*	*
FIST	40° 28' 50"	28° 52' 54"	41.983	*	*	*	*
GLCK	40° 42' 18"	29° 48' 13"	171.519	*	*	*	*
KUTE	40° 29' 05"	29° 17' 16"	500.730	*	*	*	*
MUDA	40° 18' 10"	28° 56' 29"	204.440	*	*	*	*
OLUK	40° 40' 01"	29° 35' 07"	391.329	*	*	*	*
SILE	41° 10' 46"	29° 37' 23"	49.230	*	*	*	*
TUBI	40° 47' 12"	29° 27' 02"	221.597	*	*	*	*

^a Latitude and Longitude are given in degrees (ITRF1997)

^{b1} Before earthquake observation epochs

^{b2} After earthquake observation epochs

^c Observation time

* data available ($\geq 10^h$)

3. DEFORMATION ANALYSIS

Statistical tests of linear hypothesis were applied for the deformation analysis as an important part of the inter comparison of different epochs. Each deformation analysis starts with the zero hypotheses that no deformation occurred between two successive epochs [14].

The coordinate differences and their cofactor matrices from the estimated coordinates $\hat{\mathbf{x}}_1$, $\hat{\mathbf{x}}_2$ and their cofactor matrices $\mathbf{Q}_{\hat{\mathbf{x}}_1}$, $\mathbf{Q}_{\hat{\mathbf{x}}_2}$ between the two successive GPS measurements in epoch 1 and epoch 2 are calculated using the following formulae

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

$$\mathbf{Q}_{\Delta \Delta} = \mathbf{Q}_{\hat{\mathbf{x}}_1} + \mathbf{Q}_{\hat{\mathbf{x}}_2} \quad (2)$$

Then a statistical test is performed to find the stable points between the two years period. If the null hypothesis

$$H_0: \mathbf{x}_1 = \mathbf{x}_2 \quad (3)$$

is true, the point is stable without movement from epoch 2 to epoch 1, following F (Fisher) statistic can be defined

$$T = \frac{\Delta \hat{\mathbf{x}}^T \mathbf{Q}_{\Delta \Delta}^{-1} \Delta \hat{\mathbf{x}}}{S_0^2 \mathbf{h}} = \frac{R}{S_0^2 \mathbf{h}} \sim F_{h,(f1+f2),1-\alpha} \quad (4)$$

with pooled variance

$$S_0^2 = \frac{\mathbf{v}_1^T \mathbf{P}_1 \mathbf{v}_1 + \mathbf{v}_2^T \mathbf{P}_2 \mathbf{v}_2}{f1 + f2} \quad (5)$$

where f1 and f2 are the degrees of freedom of epoch 1 and epoch 2, respectively, h is the number of independent estimates of \mathbf{x}_1 or \mathbf{x}_2 , and R is the test value of a particular point group, v is residual vector, P is weight matrix of the observations epoch 1 and epoch 2, respectively.

The hypothesis H_0 is accepted or rejected depending on whether the value of T is less or greater than $F_{h,(f1+f2),1-\alpha}$ [4, 5]. As proposed in Caspary [4], the test is so-called congruency test. The objective of a congruency test is to detect whether or not the point group of a deformation network has remained stable.

The station coordinates and their cofactor matrices were computed from free Least-Squares adjustment using the GPS baseline components and their cofactor matrices. Two methods were applied to test this congruence of the geodetic network geometries at different epochs. The first method uses an inter comparison of the station coordinates. This coordinate method works with a two-dimensional over determined congruence transformation of the coordinate set at the second epoch on to the coordinate set at the reference epoch [14].

From the directions of the horizontal displacement rates shown in Figure 2, one can easily recognize that significant motions have been found among the sites located on the two sides of the fault. TUBI and FIST are the most remarkable sites (Figure 2). The largest constant horizontal displacement rates is in the order of 8-9 mm. The fault near sites (GLCK, and OLUK) show the small but significant horizontal displacements.

A comparison of the changes in the coordinates of the sites (Figure 3) between Epoch II and Epoch III shows very large horizontal displacements of about 1.73 m at GLCK station near the epicenter of the earthquake. The remarkable horizontal displacements were also observed at other stations namely, at OLUK as about 0.95 m, and at TUBI as about 0.83 m.

In Figure 3, the fault near sites show the large horizontal displacements (GLCK, and OLUK) with the fault parallel direction whereas the far sites (MUDA, and FIST) show opposite behavior. Namely, MUDA and FIST sites located far away from the epicenter of the earthquake seem to present smaller horizontal displacements than other stations. This overall picture shows that the fault break of earthquake is finished around BADA, and CINA. The results agree with those given by Reilinger et al. [12] as expected.

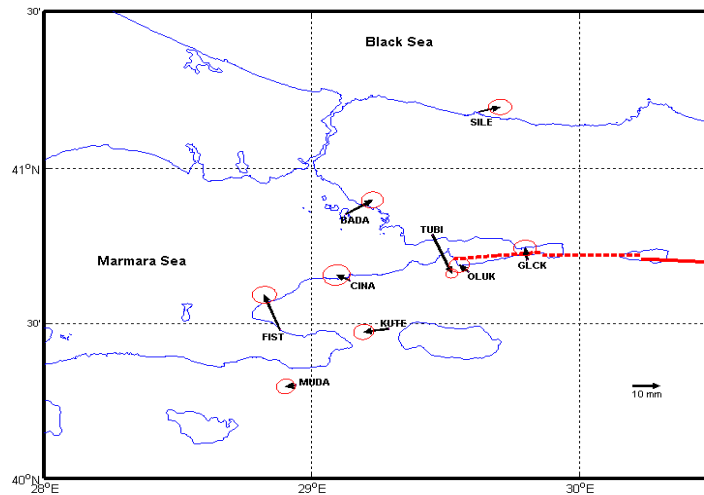


Figure 2. Horizontal displacements between Epoch I and Epoch II using the coordinate method. The 95 % confidence ellipses are drawn, and the dashed line indicates the fault geometry

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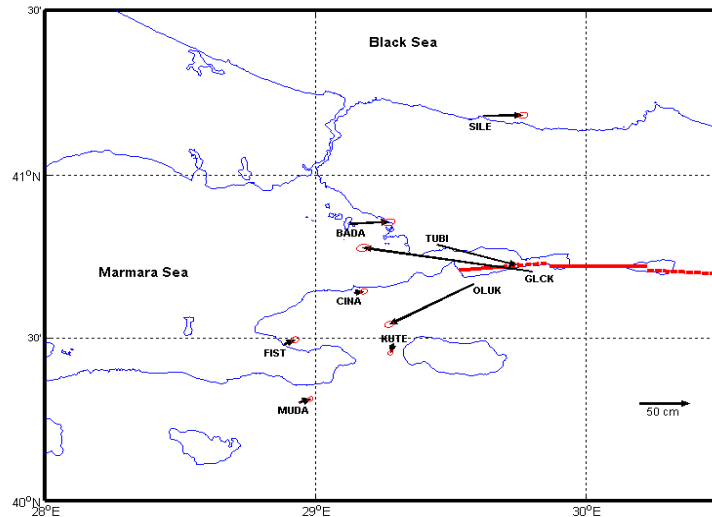


Figure 3. Horizontal displacements between Epoch II and Epoch III using the coordinate method. The 95 % confidence ellipses are drawn, and the dashed line indicates the fault geometry

Figure 4 indicates that post-seismic horizontal displacements of the stations that are determined using post earthquake Epochs (III, IV). A comparison of the changes in the coordinates of the sites shows significant horizontal displacements of about 18.8 mm at FIST station and about 15.4 mm at OLUK station, and about 8.9 mm at BADA station. However, in Figure 4, GLCK station located near the fault has significant horizontal displacement of about 8.3 mm. The rates of post-seismic deformations were larger than that of pre-seismic deformations at all sites.

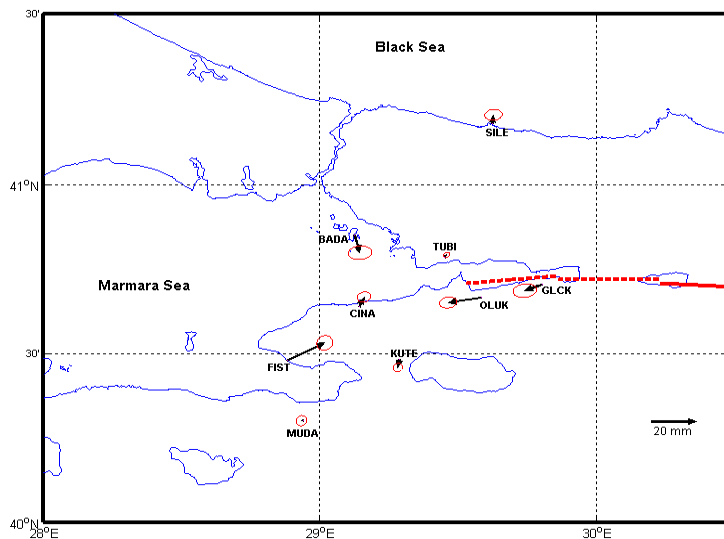


Figure 4. Horizontal displacements between Epoch III and Epoch IV using the coordinate method. The 95 % confidence ellipses are drawn, and the dashed line indicates the fault geometry

The second method to investigate changes of the network geometry is the so-called observation method. This method is completely independent from the geodetic datum of the network since the compared observations are not datum-dependent. The changes of horizontal distances, which computed as functions of the free adjusted coordinates, were compared in this particular case [14].

Tables II, III and IV show the distances of all combinations between the selected stations. Considering the corresponding standard deviations significant changes of distances can be identified.

In Table II, a comparison of the changes in the horizontal distances between Epoch I and Epoch II shows significant differences at BADA-GLCK, BADA-OLUK, GLCK-TUBI, OLUK-TUBI baselines. Also, SILE-TUBI baseline has significant extension between Epoch I and Epoch II.

Table 2. Changes of selected horizontal distances between Epoch I and Epoch II with the corresponding standard deviations (mm)

	GLCK	KUTE	MUDA	OLUK	SILE	TUBI
BADA	-5.0 (± 2.3)	0.3 (± 2.8)	4.9 (± 3.1)	-5.4 (± 2.2)	-2.0 (± 3.1)	1.9 (± 1.8)
GLCK		5.2 (± 2.9)	2.7 (± 2.8)	1.3 (± 2.6)	-2.6 (± 2.9)	-6.7 (± 1.9)
KUTE			-2.6 (± 2.8)	3.6 (± 2.9)	4.5 (± 3.2)	-4.1 (± 2.5)
MUDA				1.1 (± 2.8)	4.2 (± 3.1)	-2.4 (± 2.4)
OLUK					-0.3 (± 3.1)	-11.3 (± 1.9)
SILE						9.2 (± 2.5)

Table III indicates very large changes of selected horizontal distances between Epoch II and Epoch III because of the effects of İzmit earthquake. As can be seen from the Table III, the baseline differences for the stations GLCK and OLUK, which are close to the epicenter of the earthquake, are significantly affected by the 17 August 1999 İzmit earthquake.

From the changes of selected horizontal distances between post-earthquake epochs (III, and IV) shown in Table IV, one can easily recognize that significant differences have been found at BADA-GLCK, BADA-OLUK, KUTE-OLUK, OLUK-TUBI and MUDA-OLUK baselines. OLUK site is one of the most remarkable sites.

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Table 3. Changes of selected horizontal distances between Epoch II and Epoch III with the corresponding standard deviations (mm)

	GLCK	KUTE	MUDA	OLUK	SILE	TUBI
BADA	2093.9 (± 4.3)	-27.0 (± 4.2)	48.2 (± 4.8)	-884.9 (± 3.9)	-10.0 (± 5.1)	461.0 (± 3.3)
GLCK		-1294.3 (± 4.3)	-1441.4 (± 4.5)	-680.8 (± 4.5)	-824.4 (± 4.9)	-2537.4 (± 3.3)
KUTE			-190.2 (± 3.3)	-854.5 (± 3.9)	244.4 (± 4.3)	195.4 (± 2.9)
MUDA				-1054.1 (± 4.1)	116.7 (± 4.5)	238.4 (± 3.1)
OLUK					518.7 (± 4.8)	-915.1 (± 2.9)
SILE						98.4 (± 3.9)

Table 4. Changes of selected horizontal distances between Epoch III and Epoch IV with the corresponding standard deviations (mm)

	GLCK	KUTE	MUDA	OLUK	SILE	TUBI
BADA	-11.3 (± 4.4)	-4.5 (± 4.3)	-7.6 (± 5.0)	-18.44 (± 3.9)	7.1 (± 5.2)	-3.9 (± 3.3)
GLCK		-4.9 (± 4.3)	-7.4 (± 4.5)	6.7 (± 4.5)	4.5 (± 4.9)	-7.3 (± 3.2)
KUTE			-1.2 (± 3.3)	-9.8 (± 3.9)	8.8 (± 4.3)	5.2 (± 2.8)
MUDA				-12.9 (± 4.1)	4.5 (± 4.5)	1.2 (± 3.1)
OLUK					7.1 (± 4.8)	-8.3 (± 2.9)
SILE						3.5 (± 3.9)

4. CONCLUSIONS

GPS observations acquired in the Marmara region using pre and post earthquake epochs have been studied. The earthquake deformations have also been computed to determine crustal motions in the Marmara region using these GPS observations.

Two methods were applied to test this congruence of the geodetic network geometries at different epochs. The first method uses a comparison of the station coordinates. The second method to investigate changes of the network geometry is the so-called observation method.

The results of the analysis between pre earthquake epochs show that pre-seismic movements have an amplitude of about 1 cm and relaxation time of about 8 months at the stations. The significant motions have been found among the sites located on the two sides of the fault. The fault near sites (GLCK, and OLUK) show the small but significant horizontal displacements.

The large horizontal displacements between Epoch II and Epoch III have been found at GLCK station near the epicenter of the earthquake as about 1.73 m. The remarkable horizontal displacement is also observed at other stations namely, at OLUK as about 0.95 m, and at TUBI as about 0.83 m. The fault near sites show the large horizontal displacement (GLCK, and OLUK) with the fault parallel direction whereas the far sites (MUDA, and FIST) indicates opposite behavior. This shows that the fault break of earthquake is finished around BADA, and CINA. The analysis of the large displacements between pre and post earthquake epochs is very important in geodesy. Based on the findings given, it is easy to determine which places are affected and how large the movements are.

Rapid crustal movements after the earthquake are also observed. The results of the analysis between after earthquake epochs show that post-seismic deformation has an amplitude of about 2 cm and relaxation time about 5 months at the stations. The rate of post-seismic deformation seems to be larger than that of pre-seismic deformation at all the sites.

The significant differences in the horizontal distances between Epoch I and Epoch II have been found at BADA-GLCK, BADA-OLUK, GLCK-TUBI, OLUK-TUBI baselines. Also, SILE-TUBI baseline has significant extension. The results show very large changes of selected horizontal distances between Epoch II and Epoch III because of the effects of İzmit earthquake. The changes of selected horizontal distances between post-earthquake epochs (III, and IV) show also significant differences.

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