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Crustal Deformation Associated with the 1995 Hyogo-ken Nanbu Earthquake, Japan Derived from GPS Measurements

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A large $M=7.2$ earthquake occurred just below the western part of the Osaka-Kobe megalopolis, southwest Japan on January 17, 1995. The Japanese University Consortium for GPS Research conducted extensive local GPS measurements in and around the hypocentral region to collect near-field data on co-seismic and post-seismic crustal deformation. Adopting old GPS data collected before the earthquake, co-seismic displacement vectors have been obtained at five sites. Horizontal displacements are larger than 0.4 m in the vicinity of the earthquake fault and decay steeply with distance from the fault. The horizontal deformation pattern represents a typical right-lateral slip motion along the fault. In contrast, vertical displacements are rather difficult to interpret probably because of the low precision of old GPS measurements and the complex local site condition.

1. Introduction

An earthquake of magnitude 7.2 occurred on January 17, 1995 in the southern part of Hyogo Prefecture, southwest Japan (Figs. 1 and 2). This earthquake, named the 1995 Hyogo-ken Nanbu (southern Hyogo Prefecture) earthquake by the Japan Meteorological Agency, produced tremendous damage to the western half of the Osaka-Kobe megalopolis, especially to Kobe City and its surroundings. The earthquake was accompanied by an earthquake fault along the coastline of northwestern Awaji Island. Its strike and right-lateral motion, and the aftershock distribution extending from southwest to northeast, indicate that this earthquake occurred along active faults belonging to the Arima-Takatsuki-Rokko fault system. This system extends from the northeast of Kobe City to the northern part of Awaji Island and is considered as one of the most active fault systems in southwest Japan.

Monitoring the post-seismic transient phenomena is indispensable for research on the intraplate active faults and the total process of an earthquake. Moreover, the data will provide valuable information for the interpretation of physical properties of

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the crust and will become a basis for intraplate earthquake prediction in the future. Thus, many kinds of urgent geophysical and geological observations have been conducted in and around the epicentral area.

In detection of crustal deformation, new space geodetic techniques such as the Global Positioning System (GPS) have obtained excellent results during the last decade. For example, a nationwide continuous GPS array operated by Geographical Survey Institute (GSI), which is composed of about 100 GPS receivers distributed over Japan with a station separation of roughly 100 km, has shown the ability to reveal co-seismic crustal deformation within a few days after a large earthquake (Tsuji *et al.*, 1995). Unfortunately, the 1995 Hyogo-ken Nanbu earthquake occurred far away from stations of GSI's GPS array which means that the present array is too sparse to detect detailed near-field crustal deformations caused by the earthquake (Ishihara *et al.*, 1995).

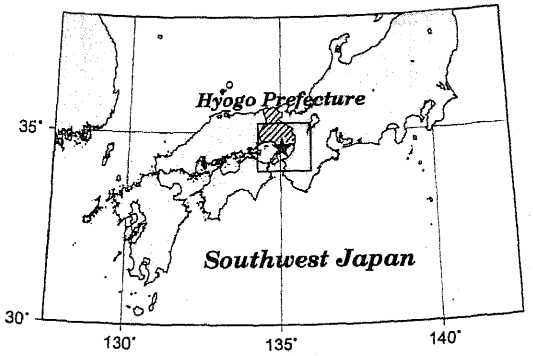

Fig. 1. Location of the epicenter of the 1995 Hyogo-ken Nanbu earthquake (star symbol). Studied area is shown by an inset box and reproduced in Fig. 2.

The Japanese University Consortium for GPS Research (referred to as JUNCO for the rest of this paper) has conducted extraordinary GPS measurements in and around the epicentral region to collect comparatively near-field data on co-seismic and post-seismic crustal deformation. This is a prompt and preliminary report concerning near-field co-seismic deformation derived from GPS measurements by JUNCO. Fault model construction, regional seismotectonic interpretation, and time series analysis of post-seismic transient deformation will be discussed in separate papers.

2. Data

Within several days after the earthquake, JUNCO deployed nearly 30 GPS stations in and around

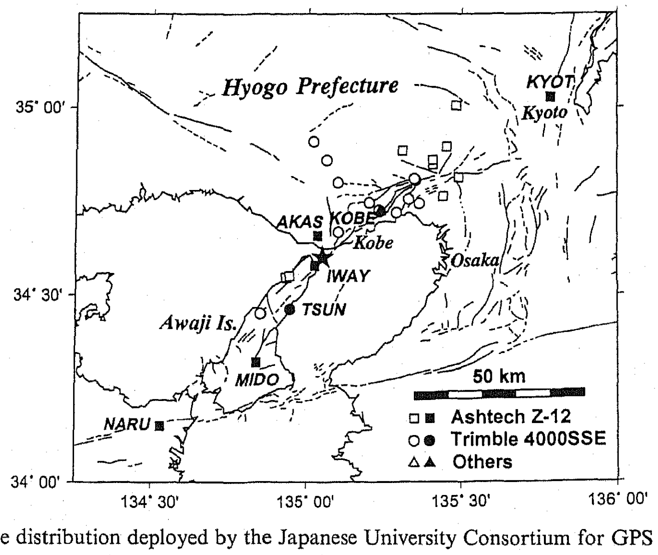

Fig. 2. GPS site distribution deployed by the Japanese University Consortium for GPS Research after the 1995 Hyogo-ken Nanbu earthquake. Closed symbols indicate stations which had been occupied before the earthquake. Star symbol indicates the location of the epicenter. Solid and dashed lines denote active faults and probable active faults, respectively (after The Research Group for Active Faults of Japan, 1991).

Kobe City and Awaji Island and started continuous GPS measurements. Figure 2 shows our GPS site locations. Static surveys were conducted at 25 sites, where 24-h data were taken at a sampling interval of 30 s for the satellite with an elevation angle higher than 15 degrees. At the other 6 sites, high rate (every second) kinematic survey data were taken as an experiment of GPS seismograph to detect short-period ground motion. Fifteen Trimble 4000 SSE, 15 Ashtech Z-12 (or its OEM by Topcon), and one Ashtech P-12 receivers, were used for these measurements. The first two are dual-band P-code receivers with a countermeasure to Anti-Spoofing (A/S), while the third is a dual-band receiver using C/A-code on L1. Details of GPS measurements conducted by JUNCO after the earthquake have been described in the general report of Hirahara *et al.* (1996).

Seven of 25 static survey sites are stations which have been occupied at least once before the earthquake. Their locations are indicated by closed symbols in Fig. 2. We will refer only to the data obtained at these seven sites because the purpose of this paper is to derive and discuss co-seismic crustal deformation associated with the earthquake. GPS measurements in question are summarized in Table 1.

Old GPS measurements were conducted at Akashi, Tsuna, Midori, Naruto, and Kyoto for the purpose of determining geoid undulation differences by GPS and leveling rather than for detecting crustal deformation (Fujimori *et al.*, 1993; Yamamoto, 1994). At each site, daily sessions of about 8 h were repeated for 2 to 4 days using a WM102 receiver.

It is very unfortunate, however, that the precision of old WM102 measurements was significantly low compared with those measurements conducted after the earthquake using new generation receivers. Sufficient lengths of observation had not been scheduled for the measurement between Akashi and Kyoto in 1989 because of the small number of satellites and poor satellite visibility. In 1993, the WM102 precision was more degraded than before, though satellite configuration was considerably improved by new satellite constellations. This is because the A/S has been continuously implemented since 1993. The A/S would mask the P-code by multiplying it by another encrypted code, while the WM102 receiver tried to use P-code on the L2 band without countermeasure against A/S. Consequently, receivers often failed to track the L2 signal during the measurements.

Fortunately, the baseline between Kobe and Iwaya had been measured by GPS just 2 months before the earthquake. Continuous data were taken over 4 days using two Ashtech P-12 receivers.

3. Analysis

All the data were processed with Bernese GPS Software Version 3.4 (Rothacher *et al.*, 1993). At present, precise satellite ephemerides must be used to derive highly precise GPS solutions even in a local survey, and they can be easily obtained via computer networks within 1 to 2 weeks after the measurement. Under the authority of the International GPS Service for Geodynamics (IGS), several analysis centers in the world collect GPS

Table 1. Site coordinates and GPS data used for the analyses of co-seismic crustal deformation associated with the 1995 Hyogo-ken Nanbu earthquake.

Sites	ID	Latitude (N)	Longitude (E)	Obs. before Eq		Obs. after Eq	
				DOY*	Year	DOY*	Year
Akashi	AKAS	34° 39′ 30″	135° 02′ 00″	308–309	1989	023–025	1995
Tsuna	TSUN	34° 27′ 42″	134° 56′ 36″	235–238	1993	026–030	1995
Midori	MIDO	34° 19′ 12″	134° 50′ 18″	235–238	1993	025–029	1995
Naruto	NARU	34° 09′ 00″	134° 31′ 48″	235–238	1993	029–031	1995
Kyoto	KYOT	35° 01′ 39″	135° 47′ 11″	308–309 235–238,	1989 1993	023–030	1995
Kobe	KOBE	34° 43′ 22″	135° 14′ 20″	328–331	1994	036–039	1995
Iwaya	IWAY	34° 34′ 42″	135° 01′ 30″	328–331	1994	036–039	1995

* Day of the year: serial day number from January 1 of the year.

data from more than 50 global sites and produce daily precise ephemerides together with weekly Earth orientation parameters. They have been combined to officially distribute to world users as IGS orbits since the beginning of January, 1994. We used IGS ephemerides to process Kobe and Iwaya data obtained before the earthquake as well as all the data after the earthquake.

Before 1994, precise ephemerides were not combined nor produced regularly among analysis centers. Fortunately, we were able to obtain precise orbits produced by Scripps Institution of Oceanography (e.g., Bock *et al.*, 1990) and apply them to process the 1993 data at Tsuna, Midori, Naruto, and Kyoto. As for the measurements at Akashi and Kyoto in 1989, there were no precise ephemerides so we applied broadcast ephemerides.

Data processing strategy was not identical between baselines. Old WM102 measurements at Akashi, Tsuna, Midori, and Naruto had been referred to the coordinates of Kyoto. It was the farthest site from the epicentral region of the 1995 earthquake and no displacements exceeding 1–2 cm had been anticipated there. Therefore, Kyoto could be treated as a local reference site to derive coseismic deformations. We computed coordinates of Akashi, Tsuna, and Midori, holding the coordinates of Kyoto fixed. Distances from Kyoto are about 80, 99, and 117 km, respectively. We similarly computed the coordinates of Naruto, about 149 km from Kyoto, but the precision of coordinates before the earthquake was too low for discussing crustal deformation.

In contrast, since both Kobe and Iwaya are located in the epicentral region, another reference site was necessary for the measurements taken at Kobe and Iwaya. Therefore, we tried to use one of the global fiducial stations as a reference site to compute their coordinates. We selected Usuda, which is located more than 320 km northeast from Kobe and is one of the IGS global tracking sites in Japan. We could obtain precise coordinates for Iwaya before the earthquake, as well as for Kobe and Iwaya after the earthquake, from long-baseline analyses with respect to Usuda. Coordinates of Kobe at the 1994 measurement, however, were not satisfactory because the L2 signal taken at Kobe was noisy and hardly applicable to the analysis. Therefore, coordinates of Kobe in 1994 were determined from L1 single-band measurement on short 22-km baseline, regarding Iwaya as a temporal reference site.

Thus, coordinates at each site were obtained for measurements before and after the earthquake and the co-seismic displacement vector was derived from their differences.

4. Results

Displacement vector components associated with the 1995 earthquake are shown in Table 2 with their standard deviation. Uncertainty of the displacement vector is due mostly to the precision of site coordinates before the earthquake, because GPS solutions after the earthquake are much more precise than the older results. The largest uncertainty is included in displacement vectors at Tsuna and Midori, that resulted from old WM102 measurements. If uncertainty can be expressed by one standard deviation, the largest uncertainties at Tsuna and Midori are estimated as about 40 mm for the horizontal component and about 40 to 50 mm for the vertical one. Displacements at Kobe and Iwaya determined from long-baseline analyses are less reliable than those of Akashi which contain the results of the oldest measurement.

Horizontal displacement vectors are drawn in Fig. 3 with 95% confidence ellipses (2.45 times one standard deviation). Very remarkable displacements were observed at sites located in the vicinity of the earthquake fault, 0.40 m at Akashi, 0.45 m at Iwaya, and 0.35 m at Tsuna, respectively. Displacements at these three sites are far larger than their 95% confidence limit. In contrast, displacement seems to decay rapidly with distance from the earthquake fault.

The observed vertical deformation pattern seems more complicated than the horizontal one. While a small amount of subsidence was observed at Iwaya, upheavals larger than the subsidence at Iwaya were

Table 2. GPS-derived displacement vector associated with the 1995 Hyogo-ken Nanbu earthquake.

Sites	North (m)	East (m)	Vertical (m)
Akashi	0.360 ± 0.002	0.171 ± 0.007	0.144 ± 0.007
Tsuna	−0.352 ± 0.029	−0.018 ± 0.041	0.218 ± 0.049
Midori	−0.081 ± 0.022	−0.015 ± 0.032	0.130 ± 0.040
Kobe	0.019 ± 0.004	−0.014 ± 0.012	0.133 ± 0.023
Iwaya	−0.059 ± 0.004	−0.449 ± 0.013	−0.025 ± 0.024

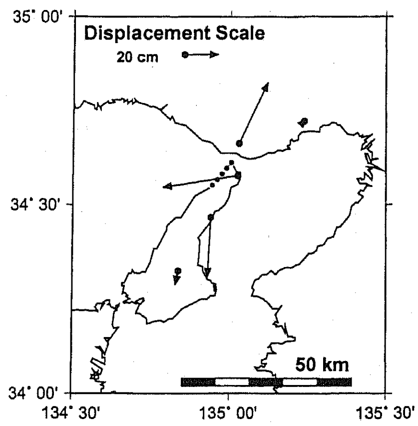

Fig. 3. Horizontal displacement vectors with 95% confidence ellipses (2.45σ). Dotted line indicates the surface trace of the earthquake fault.

detected at the other four sites. The deformation pattern is hardly explained by a simple block motion across one fault plane.

5. Discussion

Surface rupture that appeared on Awaji Island showed a typical right-lateral slip motion of up to 1.2 to 1.3 m (e.g. Suzuki *et al.*, 1995), and this motion is clearly reflected on the horizontal deformation pattern in Fig. 3. According to the regional co-seismic deformation field detected by GSI's nationwide continuous GPS array (Ishihara *et al.*, 1995), horizontal displacement decayed steeply away from the hypocentral region. The maximum displacement detected by the GSI's array, which was observed at the station located about 47 km away from, but nearest to the epicenter, was smaller than 0.04 m. GSI's results imply that displacement exceeding 1–2 cm is not anticipated at Kyoto, which is more than 80 km away from the epicenter. Thus, our selection of reference sites for GPS measurement, Kyoto and Usuda, was adequate and the deformation pattern in Fig. 3 may be invariant.

Surface rupture also indicates uplift of southeastern block (most of northern Awaji Island) relative to the northwestern block. However, the amount of vertical offset is not uniform along the trace, it varies roughly from 0.3 to 1.3 m at site to site within a distance less than 10 km (Suzuki *et al.*, 1995). This means that observed vertical deformation may be more or less affected by local site effects. Moreover, the precision of the vertical component in GPS measurement is generally twice to three times worse than the horizontal component. In particular, the precision of the old GPS measurements taken before 1993 was low because of the poor satellite configuration and the Anti-Spoofing. Taking these conditions and our sparse site distribution into account, we are unable to derive as much information on vertical deformation as horizontal deformation.

No earthquake fault appeared on the surface at the Kobe side of this earthquake though many quaternary active faults had been discovered beneath this area (The Research Group for Active Faults of Japan, 1991). However, leveling along the coastline on the Kobe side before and after the earthquake, revealed remarkable vertical movements (Ishihara *et al.*, 1995). When Himeji (i.e. the western end point of this leveling root about 28 km northwest from Akashi GPS site) is fixed, upheaval increases steeply toward the southeast and reaches a maximum of about 0.18 m in the western part of Kobe City. The Akashi GPS site is located close to this maximum upheaval and GPS-derived vertical displacement at Akashi, with an upheaval of 0.14 m, is consistent with the leveling result. In contrast, the eastern half of the leveling route shows a small amount of subsidence and this is not consistent with the upheaval of 0.13 m observed at the Kobe GPS site. The deformation pattern in this area may be complicated but we can derive no more informaon from our sparse site distribution on the Kobe side. How far the focal plane extends under the Kobe area, and which part of the quaternary active faults under this area made a contribution to the occurrence of this earthquake, are probably the main problems still under discussion.

Yoshida *et al.* (1996) used data obtained in this study to examine the fault model using the inversion technique, together with GSI's GPS and leveling results and strong motion records. They assumed there are two fault planes on Awaji Island and in Kobe City according to aftershock distribution, quaternary active faults distribuon, and crustal deformation pattern. Their results show that the slips are large in the vicinity of the hypocenter and in the shallow part of the fault plane of the Awaji side, while the slip in the shallow part of the Kobe side is not remarkable. The deformation derived from our GPS measurements is well reproduced by using their fault model.

6. Conclusions

The Japanese University Consortium for GPS Research conducted extraordinary GPS measurements in and around the hypocentral region of the 1995 Hyogo-ken Nanbu earthquake ($M=7.2$) to collect near-field data on co-seismic and post-seismic crustal deformation. Adopting old GPS data collected in this area before the earthquake, co-seismic displacement vectors have been obtained at five sites from coordinate differences before and after the earthquake.

Horizontal displacement vectors represent a typical right-lateral slip motion along the earthqake fault. In contrast, quantitative interpretation of vertical displacements is rather difficult because of the low precision of old GPS measurements, insufficient site distribution, and complex conditions associated with local sites.

Overall GPS activity by the university group as well as the post-seismic transient deformation observed by this survey are discussed in separate papers in this volume (Hirahara *et al.*, 1996; Kato *et al.*, 1996).

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