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IMPACT OF A LARGE EARTHQUAKE ON A GPS NETWORK: THE CASE OF THE 1999 CHI-CHI, TAIWAN EARTHQUAKE

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ABSTRACT

On 20 September 1999, Taiwan was hit by the largest inland earthquake (M_w=7.6) in the last century, resulting in an 80-kilometer thrust rupture almost directly along the existing Chelungpu fault. Here, we estimated the coordinates of the GPS stations by using the annual epoch-observed and permanent continuously-recorded GPS data covering the 1992-1999 period. Taking into account the effects of secular motion and post-deformation, we calculated the corrected coseismic displacements. Relatively large coseismic displacements of 8-9 m in the horizontal and vertical components were found in the northern part of the fault. Stations on the hanging wall shifted horizontally 2-9 m in the NW direction and decreased in magnitude from west to east. On the other hand, displacements on the footwall were less than 2 m in the SE direction but increased from west to east. The size of the zone overlapping the hanging wall and the footwall showed a decrease of 796 ppm in 494 km^2. This is in direct contrast to areas near the fault which increased in size from 13 to 237 ppm. Significant postseismic deformations were also observed in data from the existing 44 permanent stations and 7 temporary stations. Additionally, large postseismic deformations of 10-20 cm were found at stations SUNM, I007 and YUSN within 10 months.

INTRODUCTION

On September 20, 1999, a devastating earthquake occurred in the central part of Taiwan. With a moment magnitude (M_W) of 7.6, the event had a focal depth of about 8 km **[4,5]**. Since its epicenter was located approximately 5 km northeast of the town of Chi-Chi, Nantou county, Taiwan, the earthquake was given the name, the 1999 Chi-Chi earthquake, by the Central Weather Bureau (CWB), Ministry of Transportation and Communication **[1]**. This event claimed more than 2,400 lives and caused extensive structural damage. The surface rupture amounted to about 80 km in total from north to south and was well exposed along the existing Chelungpu fault. From a seismological point of view, the Chi-Chi earthquake was a typical thrust fault: a strike and left-lateral faulting system with a dip angle of 30 degrees. The strong motion data indicate that the peak ground acceleration exceeded 0.5 g at many sites and even rose to as high as 0.9 g at others. The integration of the strong motion data revealed that the horizontal displacement was about 9 m in the northwest direction and that there was a 3.4 m uplift **[2]**. Many other geologists have reported similar results based on different field surveys **[1,2]**.

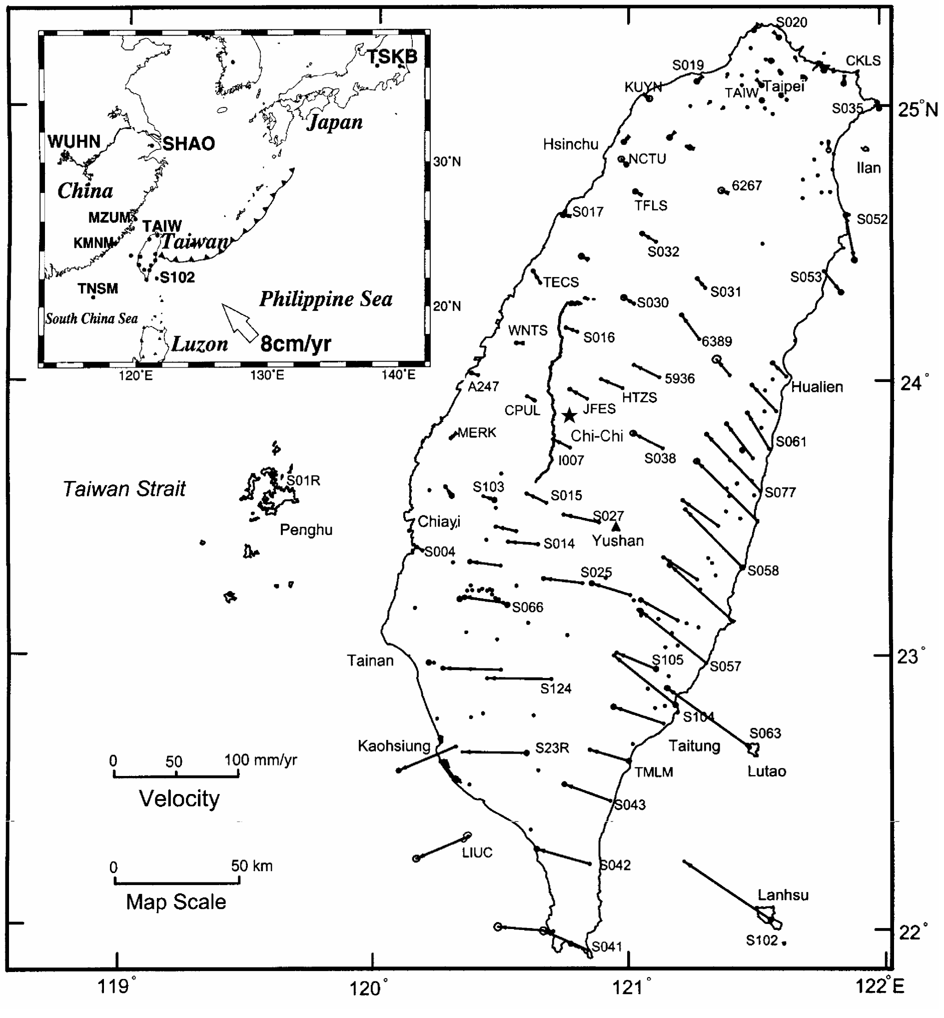

Figure 1. GPS stations in Taiwan. The small dots represent annual-surveyed stations; only some of the velocities are shown here. The velocities of the GPS stations were estimated relative to Penghu (S01R). The 95 % confidence ellipse is plotted at the tip of each velocity vector. The star symbol stands for the epicenter of the main shock nearby the town of Chi-Chi. The bold zipped line close to the epicenter is the Chelungpu fault ruptured by the 1999 Chi-Chi earthquake.

Since 1990, the Institute of Earth Sciences (IES), Academia Sinica has had about 200 GPS stations installed to monitor crustal deformation in the Taiwan area (Figure1), but as their studies have primarily focused on the southern and eastern parts of Taiwan, only 18 stations were distributed in the vincinity of the Chi-Chi earthquake. The GPS instruments, nevertheless, were set up 8-10 times between 1990 and 1999 at those stations. However, in that the average distance between the stations was about 20-30 km, the network was not dense enough to resolve local deformation. Thus, it would be necessary to increase the number of GPS stations to be able to detect the detailed features after the preliminary analysis.

Fortunately, the Central Geological Survey (CGS), Ministry of Economic Affairs had installed 50 stations on both sides of the Chelungpu fault to monitor crustal deformation. GPS-surveying was carried out once a year starting in January 1998, with each site occupied at least 2-3 times during each annual campaign. Additionally, a 40-station GPS study, covering the complete rupture zone, was conducted by the Ministry of Interior (MOI) in January 1997. As the IES decided to re-measure all of the stations around the fault the day after the mainshock, most of the CGS and IES stations were occupied 1-3 times within 15 days of the mainshock, and still another large study at the CGS, IES and the MOI stations was undertaken within the next 3 months, as well.

To observe postseimic deformation, 7 continuously-recorded GPS stations were soon installed by the IES in the deformed area, 3 on the footwall and 4 on the hanging wall. It should be noted that these GPS stations will continue their operations for another 1-2 years in order to provide a complete understanding of the deformation processes and their mechanisms. In the present study, the data obtained from all of the existing permanent GPS stations were analyzed with the focus on the coseismic effects on the coordinates of the control points, and reference frame.

GPS DATA AND PROCESSING

Generally, most of the Taiwan GPS stations are located on the top of mountains or at secure places with good sky visibility. The GPS data from both the CGS and the IES were observed for geophysical purposes. To ensure high precision, most stations were occupied 2-3 times in each annual surveying with 7-hour sessions for the CGS and 6- to 14-hour sessions for the IES stations. Though the observed session was only 4-5 hours in duration at the MOI stations, these data were used to establish the control network. The GPS data observed by these three institutions before and after the mainshock are presented in Table 1. The CGS, IES and MOI used Trimble 4000SSE/SSi dual frequency receivers to collect annual GPS data with a 15-second sampling rate and a 15° cut-off angle after the mainshock.

To monitor crustal deformation, plate motion and the change in the reference frame, 44 permanent GPS stations have been installed, 16 by the CWB, 17 by the IES, 8 by the MOI and 3 by other institutions since 1991. These stations are equipped with

25 Rogue , 6 Leica CRS1000 and 13 Trimble receivers that record 24-hour data daily at a 30-second sampling rate. Most data are transferred by Internet, telephone or occasionally by mail.

Table 1. *Observed GPS data.*

Year	Day of Year	Span (hr)	Institution
1997	025-031	4 – 5	MOI
1999	005-021	6 – 7	CGS
1999	203-204	14	IES
1999	266-284	6 – 14	CGS IES
1999	291-307	4	MOI IES
1999	347-355	14	MOI IES

All available GPS data from rover and permanent stations were processed session-by-session with Bernese GPS software version 4.0 **[6]** to obtain the daily solutions. In the first stage, the ambiguities were estimated and fixed to integer by using the Quasi Ionosphere Free (QIF) strategy. The IGS ephemerides, earth rotation parameters and the fixed ambiguities were assumed to be the known parameters in the processing of the GPS data. Finally, L3 that is the ionosphere-free combination of the L1 and L2, was used to estimate all coordinates and the 2-hour interval tropospheric zenith delays. For permanent GPS data, including the Taiwan tracking network and a few IGS stations offshore, the daily solutions were determined, but in the processing stage, no attempt was made to adjust the results to a campaign solution using the common adjustment method. Since the duration of each annual surveying was about 2 weeks, a campaign solution was performed by stacking all of the daily normal equations of the rover and permanent stations. Based on previous studies **[7,8,9]**, all of the GPS results had a precision range of 3-5 mm in the horizontal component and 10-15 mm in the vertical component.

COSEISMIC DISPLACEMENTS

In order to investigate the inland crustal deformation of Taiwan, we usually estimated the relative velocity by selecting the S01R as reference station. The velocity of S01R relative to Euroasian plate station(WUHN) is only 3-4 mm/y**[8]** to the west, the S01R could be thought as reference station. But, a large displacement, about 2 cm, was found at S01R, so it was not suit for using it as reference in this study. An IGS station, WUHN, was selected as the reference station for the estimation of the relative coordinates of stations in Taiwan. Due to its location at about 1,000 km northwest of

Taiwan (Figure 1), the coordinates of WUHN, it was thought, should not have been affected by the Chi-Chi earthquake. In fact, after comparing several daily solutions, no significant changes were found at two other IGS stations, SHAO and TSKB, near the Taiwan area, which qualified them to serve as quasi-stable sites. However, the coordinates of WUHN did not change at all either before or after the mainshock, making it the most ideal reference station.

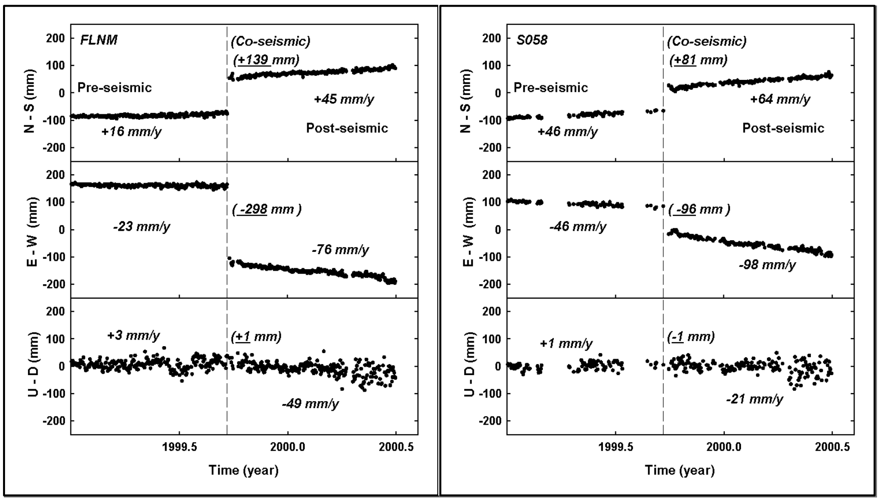

Figure 2. Preseismic, coseismic and postseismic deformations of two permanent GPS stations, FLNM and S058, associated with the 1999 Chi-Chi earthquake. The values of coseismic displacements are in parentheses. The dashed line represents the epoch of the 1999 Chi-Chi earthquake.

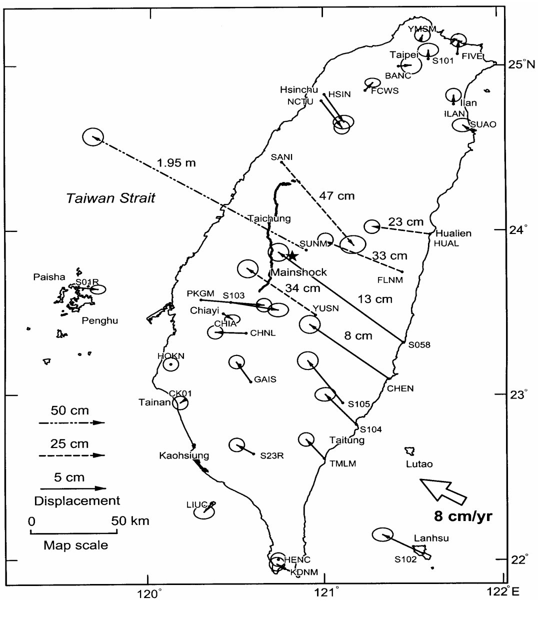

Figure 3. Coseismic displacements of permanent stations associated with the 1999 Chi-Chi earthquake. Due to large displacements, some of the vector scales changed. The dashed lines needed to be enlarged. The 95% error ellipse is plotted on the tip of the displacement vectors.

A comparison of the changes in the coordinates of the permanent GPS stations (Figure 2) before and after the event shows significant displacements of 0.33 m with an azimuth of 294° at FLNM and 0.13 m with an azimuth of 310° at S058. The rate of post-seismic deformation was larger than that of pre-seismic deformation at both of these sites.

All of the coseismic displacements at permanent stations are plotted in Figure 3. A very large displacement of about 1.95 m in the N59° W direction was found at SUNM station near the epicenter. Remarkable displacement was also observed at other stations: 0.47m with an azimuth of 143° at SANI, 0.23 m with an azimuth of 278° at HUAL and 0.34 m with an azimuth of 309° at YUSN. Most of the coordinates at stations located within 100 km of the epicenter changed a few centimeters in this event. Only stations located in the northern and southwestern parts of Taiwan seem to have been only slightly affected by the 1999 Chi-Chi earthquake.

The coseismic offsets of the epoch-occupied stations in the vicinity of the Chelungpu fault were also estimated. After considering secular crustal motion and postseismic deformation, the displacements were corrected using the equation:

$$Xc = Xj + (Tj - Tq)*V - Xi - (Tq - Ti)*V + Cp, \quad (1)$$

where Xc is the corrected displacement at epoch Tq that the earthquake occurred; Xj and Xi are the coordinates measured in epoch Tj (after the quake) and Ti (before the quake); V is the velocity derived from 1992 to 1999 GPS data; and Cp is the correction of postseismic displacement estimated from both the 7 temporary continuous tracking GPS stations and the reoccupied stations **[8]**. Some of the corrected displacements are shown in Figure 4.

The sites located on the hanging wall (i.e. on the eastern side of the fault) moved a few meters to the northwest. The largest offset was found near the northern part of the fault at station M324 which moved 9.08 m with an azimuth of 338° and 3.97 m upwards. The increasing horizontal displacements, from south to north, were 3.33m with 309° at G044, 4.68m with 304° at AF22 and 6.68m with 323° at AF25. From west to east, the decreasing horizontal movements were 3.41 m, 2.72 m, 2.28m and 1.76 m at stations AF30, JFES, HTZS and 5936, respectively. A relatively large vertical movement was evident near the fault and was sinuously degrading from west to east.

In contrast, the sites on the footwall (i.e. the western side of the fault) moved less than 2 meters in the SE direction and showed a downward offset. Simply put, the closer the stations were to the fault, the larger their movements were.

In this study, the focus was on determining coseismic displacement. The implications of the coseismic displacements associated with the 1999 Chi-Chi, Taiwan earthquake are discussed in detail elsewhere **[3,9].**

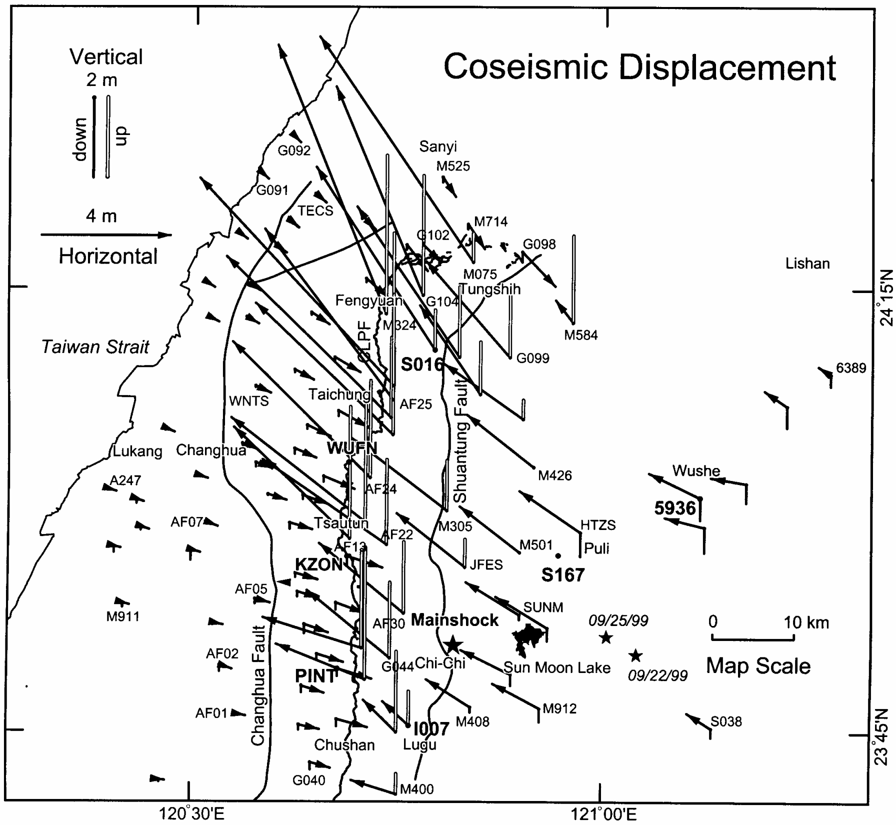

Figure 4. Coseismic displacements at stations in the epicentral zone of the Chi-Chi earthquake. Star symbols stand for two large aftershocks with magnitudes (M_w) of 6.4 and 6.2. The stations with boldface are the temporary sites to monitor postseismic deformation. The CLPF represents the Chelungpu fault.

AREA CHANGE

According to the previous analysis, the hanging wall moved in the NW direction and compressed against the footwall. Therefore, the size of the fault area must have decreased due to overriding. Larger movements were found at stations near the fault and vice versa, implying that rate of movement in the area was not uniform. Therefore, to analyze the change in the area size (shown in Table 2), we divided the deformed zone into 7 striped blocks, each parallel to the main fault (Figure 5). In Figure 5, A and dA represent the size of the blocks and their change in size, respectively. The term, dA, is the difference in the area measured before and after the mainshock. Table 2 shows that the size of the central block, M1, with a total area of 80 x 6 km^2, decreased 393,662 m^2. With respect to cadastral surveying, the decreased amount, equivalent to about 800 ppm, was too large, therefore necessitating the re-surveying of this block.

Table 2. Size of each block and change (increase/decrease) in the deformed area.

Block	Size of Block (A) m^2	Change in size (dA) m^2	(dA/A) ppm
M1	494,319,441	-393,662	-796
R2	703,226,407	+167,353	+238
R3	551,627,195	+52,966	+96
R4	473,116,913	+24,282	+51
Q4	505,956,230	+564	+1
L5	434,749,108	+23,209	+53
L6	743,227,405	+21,527	+29
L7	665,665,965	+8,647	+13

On the footwall, the area increased 13, 29 and 53 ppm in blocks L7, L6 and L5 respectively, whereas on the hanging wall the area increased 51, 96 and 237 ppm in blocks R4, R3 and R2, respectively. The area of block Q4 increased only slightly, about 1 ppm. The stretching deformation in blocks L5, R2, R3 and R4 was still too large which again required a re-surveying of the boundaries of land.

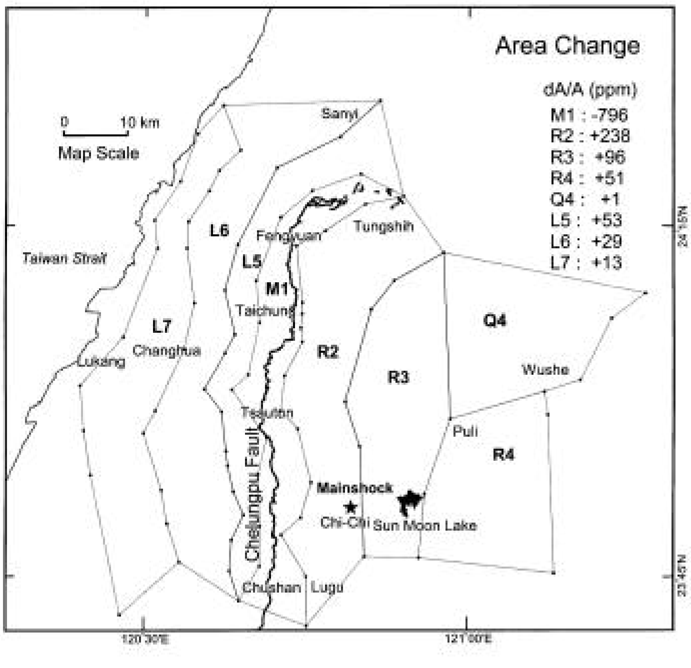

Figure 5. Area changes in the deformed zone. Blocks L5, L6 and L7 are located on the footwall, while blocks R2, R3, R4 and Q4 are on the hanging wall. The block M1 represents for the overriding zone.

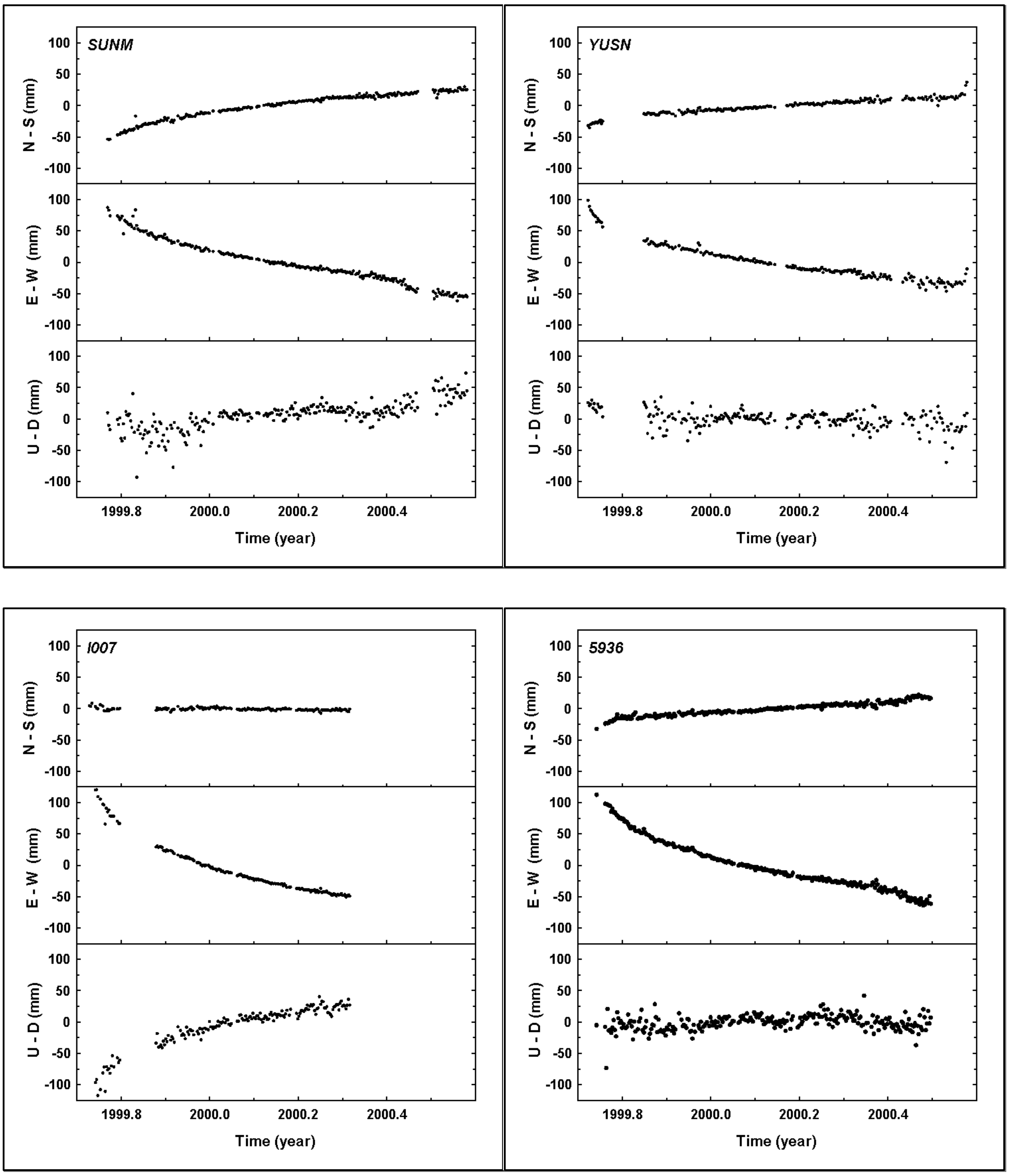

Figure 6. Postseismic deformation of permanent GPS stations associated with the 1999 Chi-Chi earthquake. Stations SUNM and YUSN are close to the fault and are located on the hanging wall. I007 and 5936 were temporarily installed to monitor postseismic deformation.

In this paper, the variations in the coordinates at the permanent stations after the Chi-Chi earthquake are presented in Figure 6. It is obvious that the rate of movement at stations SUNM, YUSN, 5936 and I007 was relatively fast in the initial stage of postseismic deformation but that it eventually slowed down within a few months. The other sites, FLNM, S058, S016 and S167, showed a similar trend of movement with a total displacement of about 10-20 cm at each site over a 10-month period. The rate of postseismic deformation was much larger than that of preseismic deformation(1-2 cm/y).

Three sites on the footwall, namely PINT, KZON and WUFN , moved slightly, about 2 cm in the SEE direction within 10 months. Although the implications of postseismic deformation are not the focus of this paper, the geophysical characteristics are very important for a better understanding of rheology. This will be discussed in detail in a future publication after the re-occupied campaign has been conducted a number of times in next year or two.

DISCUSSION AND CONCLUDING REMARKS

For permanent stations, the largest coseismic displacement was found at SUNM, near the epicenter, with a horizontal displacement of 1.95 m with an azimuth of 301° subsiding at 0.14 m. Station YUSN, located on the highest mountain in Taiwan, moved horizontally 0.34 m with an azimuth of 308° and 0.07 m downwards. Stations about 80-100 km from the Chelungpu fault in the eastern margin of the Central Range (FLNM, HUAL) and in the Coastal Range (S058) had a horizontal displacements of 0.33 m, 0.23 m and 0.13 m with azimuths of 294°, 278° and 310°, respectively. Displacements at sites S102, TMLM, S104, S105 and CHEN in southeastern Taiwan were in the range of 2-8 cm.

In southwestern Taiwan, station CHNL, located south of the Chelungpu fault, showed only a 2.8-cm horizontal displacement with an azimuth of 272°. To the southwest of the Chelungpu fault, stations PKGM, CHIA, S01R and S103 moved 1.7-4.9 cm with azimuths of 96°-101°. No significant displacements were found at other stations in southern Taiwan (HOKN, CK01, S23R, KDNM, S106 and S011), northern Taiwan (YMSM, S101, BANC, FIVE, SUAO and ILAN) or near the Chinese continental margin (KMNM and MZUM).

From the continuously-recorded and epoch-surveyed GPS data, significant afterslips were found at the sites on the hanging wall of the Chelungpu fault. The most accurate coseismic displacements were plugged into the dislocation model, which yielded more precise results. To estimate coseismic displacement, postseismic and secular corrections were necessary for the epoch-surveyed sites occupied after the mainshock.

Though the geophysical interpretations of the findings are not presented in this paper, the analysis of large coseismic displacements is very important with respect to geodesy. Based on such information, it is easy to determine which places are affected and how much the movements are. The area with increases and decreases can be identified and changes in land boundaries near the fault can be well clarified. For this reason, the MOI, as the geodetic network manager, made wise use of this to re-survey parts of the whole network. Preliminary coseismic displacements were estimated within one week by using the data from rover sites and permanent stations. The MOI also decided to re-measure the central and eastern parts of the geodetic network in the middle of October 1999 and finished the fieldwork within 2 weeks. After publishing the re-measured coordinates of control points in November 1999 **[10]**, the surveyors had a good and reliable reference frame for cadastral surveying.

With the experience gained from this event, the present authors would like to advise potential geoscientists that after a mainshock, making a plan and collecting data should be done as quickly as possible. Otherwise, certain features of rupture may be destroyed due to rescue or reconstruction efforts after the mainshock. It is necessary to supply immediate precise coordinates in a short time. In fact, in this case, the MOI completed the photography of the damaged areas and scanned all the photos in the few days which followed. The digital photos were, therefore, available for rescue efforts within 24 hours after the mainshock.

ACKNOWLEDGEMENTS

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