ESTIMATES OF HORIZONTAL DISPLACEMENTS ASSOCIATED WITH THE 1999 TAIWAN EARTHQUAKE

C. C. Chang

Department of Surveying and Mapping Engineering

Chung Cheng Institute of Technology, Taiwan, ROC

ABSTRACT

A total of ninety-nine GPS control sites were measured by GPS after the 1999 Chi-Chi earthquake (Mw=7.6) occurred in Central Taiwan, in order to estimate the surface displacements and provide 'new' coordinate data set for government to carry on the re-construction scheme in the damaging area. GPS data observed at these sites were processed, and the network solutions showed the coordinate accuracy of 3 - 4 cm in horizontal components. The coordinate data was also compared with those measured before the earthquake to investigate the displacements. The estimates showed the horizontal displacements of 0.1 m to 8.5 m for the sites observed. It was also found that the significant displacements extended along the Chelungpu active fault, where an obvious fault trace ruptured at the earthquake has been clearly seen.

INTRODUCTION

A magnitude-7.3 (Mw=7.6) earthquake rocked central Taiwan on 21 September 1999 (see Figure 1). This earthquake is believed to be the strongest one over the last century in the Taiwan area. Within two minutes of shaking at the early morning (01:47:12.6 Local Time), near 25,000 buildings collapsed, 7,000 people injured, and more than 2,000 people were killed in the earthquake. This earthquake, occurred at Chi-Chi township (23.85°N, 120.78°E), was located between the Chelungpu and Shuantun faults. The surface rupture from the earthquake extended for around 85 km along the Chelungpu active fault with vertical thrust and left lateral strike-slip offsets **[3]**.

The Chelungpu thrust fault is one of the major geological structures in the west-central Taiwan. It spreads approximately along the eastern margin of the Taichung basin and extends north-southwards. Based on the GPS monitoring data conducted by the Academia Sinica over the last 5 years, it showed that the velocity field in this region was around 1.5 - 2.0 cm/year west-north-westwards. It was also found to be one of the areas with the significant accumulation of crustal strain. However, most seismic activity has frequently appeared on the southeastern side of the island due to the collision of two different tectonic plates. A significant moving rate of 7 - 8 cm/year towards northwest direction has been monitored using GPS in this collision zone **[4]**. Therefore, the so-called 1999 Chi-Chi earthquake, acted along the Chelungpu fault, was generally believed to be out of the prediction.

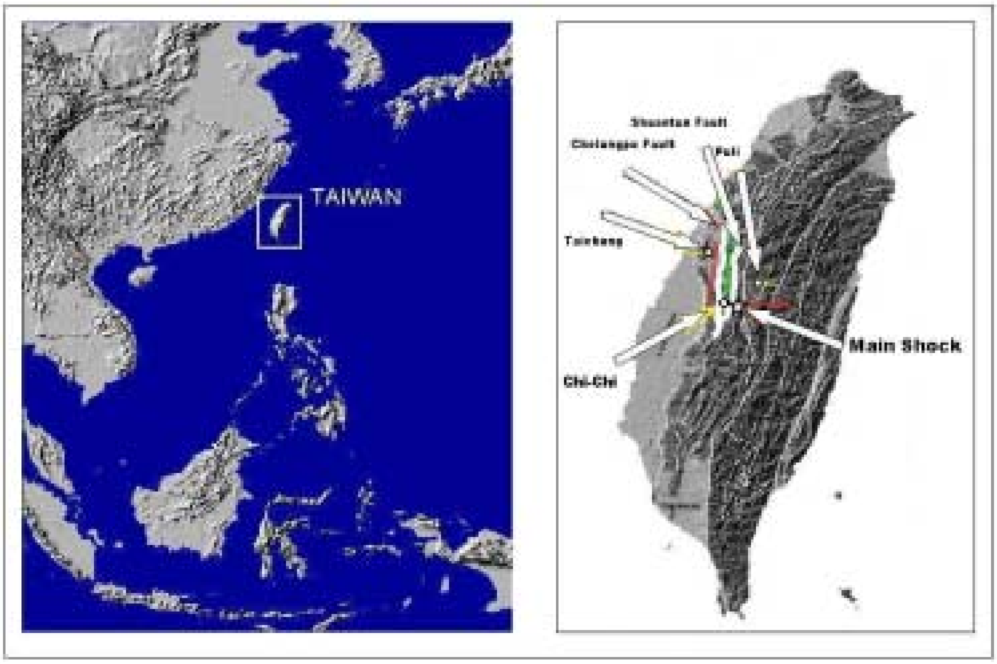

Fig. 1. Location of epicenter (provided by the Central Geological Survey)

A significant level of surface displacements, probably the largest land movements ever found for modern earthquakes, has been clearly seen along the Chelungpu fault after the Mw 7.6 mainshock and other five aftershocks of magnitude greater than 6.0 in those three weeks. The realization of changes of geodetic coordinates for control stations in the earthquake area became very important, as the re-construction scheme had to be effectively executed by the government, when extensive shaking was eased.

GPS has been the most precise and convenient technique in geodetic surveying over the last 20 years. Due to its high positioning accuracy and effectiveness of extending the working range, GPS has now almost entirely surpassed terrestrial methods for high precision geodetic works. Hence, a survey team organised by Chung Cheng Institute of Technology (CCIT) was dispatched to use GPS to determine the coordinates for the selected sites in the earthquake area. The field campaign, as part of official re-construction scheme, was aimed at providing the 'new' coordinates and investigating the surface displacements for other planning works. It was also expected to constitute one complete data set for this damaging earthquake to help geodesists, seismologists, and geologists understand the complex patterns associated with the earthquake.

FIELD CAMPAIGN AND DATA PROCESSING

A total of ninety-nine control stations in the earthquake area, set up by the Bureau of Land Survey and used for cadastral survey, were proposed to measure by the CCIT GPS team. The stations measured by the GPS campaign are shown in Figure 2. The GPS observations for this campaign were carried out from 18 October 1999 to 27 October 1999 over ten successive days. Three Ashtech Z-Surveyor receivers and two Leica SR-9500 receivers were deployed at those GPS control sites, with two 3-hour sessions in one day. Two photos depicting the GPS fieldwork with the damage of earthquake to terrain and construction are shown in Figure 3. During the GPS campaign, data was also obtained from one permanent tracking station in USUD (Japan). This IGS station was held fixed during the data processing, instead of using eight official GPS tracking stations located in the Taiwan area **[2]**. The reason was based on the assumption that those tracking sites in Taiwan were somewhat moved by such a strong earthquake as well.

The GPS network solutions were carried out using the commercial GPS software. The IGS precise ephemeris was used to provide the satellite orbit information in the data processing. During the ten-day GPS observations, the IGS precise ephemeris used were for GPS week 1032 and 1033, respectively. A summary of the options used in the data processing is given in Table 1.

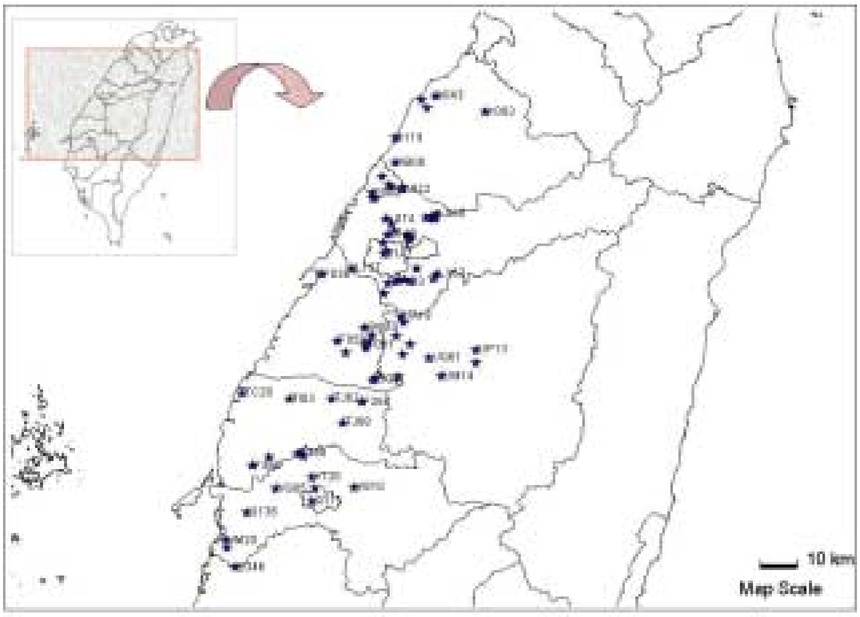

Fig. 2. Control stations measured by the CCIT GPS team after the earthquake

Fig. 3. Photos taken during the GPS campaign

Table 1. *Data processing options for the GPS solutions*

Reference Frame Definition	
Stations Fixed:	USUD
Coordinate Source:	ITRF97 GPS Stations **[1]**
Tectonic Plate Model:	ITRF97 Velocity Field **[1]**
Reference Epoch:	1999.81
Models Applied	
Ionospheric Delay:	L1/L2 Frequency Combination
Tropospheric Delay:	Modified Hopfield Model
Antenna Phase Center:	NGS Model
Adjusted Parameters	
Data Sessions:	10 day x 2 session / day x 3 hours / session
Stations:	Position (X,Y,Z) of GPS Control Stations
Satellites:	Fixed to IGS Precise Ephemeris
Ambiguities:	Integer Free

ESTIMATION OF INTERNAL ACCURACY

Once GPS solutions have been obtained, e.g. 20 independent single-session network solutions, the coordinate agreement based on the same sites measured in different sessions can be performed as an indicator of internal accuracy. The so-called session-to-session agreement, also seen as the coordinate discrepancy between the two single-session GPS solutions for the same site, is theoretically in a centimeter level.

As there was time pressure to carry out the GPS campaign for the earthquake re-construction scheme, the GPS networks were not so well-designed to achieve the highest accuracy. Therefore, only three sites were found to be re-occupied by any two of the sessions. It must be admitted that the analysis of internal accuracy based on only three stations each occupied in two sessions is hardly a convincing statistical estimate. However, it is the only indicator to show the accuracy obtained by the GPS campaign. The three-dimensional coordinate agreements between the two different sessions are now listed in Table 2.

Table 2. *Session-to-session coordinate agreements for the GPS solutions*

Station	N (cm)	E (cm)	H (cm)
K067	0.5	0.6	2.1
L102	2.1	4.9	0.6
L121	6.8	2.7	9.5
RMS	4.1	3.2	5.6

The session-to-session coordinate agreements represent the quality of the solutions from the ten-day GPS observations, with the RMS (root-mean-square) agreements of 4.1 cm in North component, 3.2 cm in East component, and 5.6 cm in height. This level of coordinate agreement is apparently not competitive with those achieved by the high accuracy GPS. The explanation may be the low quality of observation condition at those sites, and the long distance between the fixed and unknown stations. However, it is still capable of using these coordinates to estimate the surface displacements significantly moved by the strong earthquake.

HORIZONTAL DISPLACEMENT

When two sets of coordinate measured at the same station but different times are compared, changes in three-dimensional coordinate can be basically used to realize the surface displacements. As the coordinate data set for third-order GPS stations in the earthquake area had been archived during the period of 1995 - 1998, the coordinates for those sites observed by this time of GPS campaign can then be compared to estimate the surface displacements caused by the earthquake.

Two coordinate data sets based on the same datum but measured before and right after the earthquake, respectively, were found to have sixty-four common points in the area. However, only horizontal components were obtained to investigate the surface displacements, as the prior coordinate data set was mainly used for cadastral survey and provided with only 2-D coordinates. Therefore, the estimates of horizontal displacement caused by the earthquake are now summarized in Table 3 and shown in Figure 4 for those common sites.

Table 3. *Estimates of horizontal displacements*

Statistical	N (cm)	E (cm)	2D-Circle (cm)
Minimum	2.6	4.4	9.9
Maximum	793.4	406.0	858.7

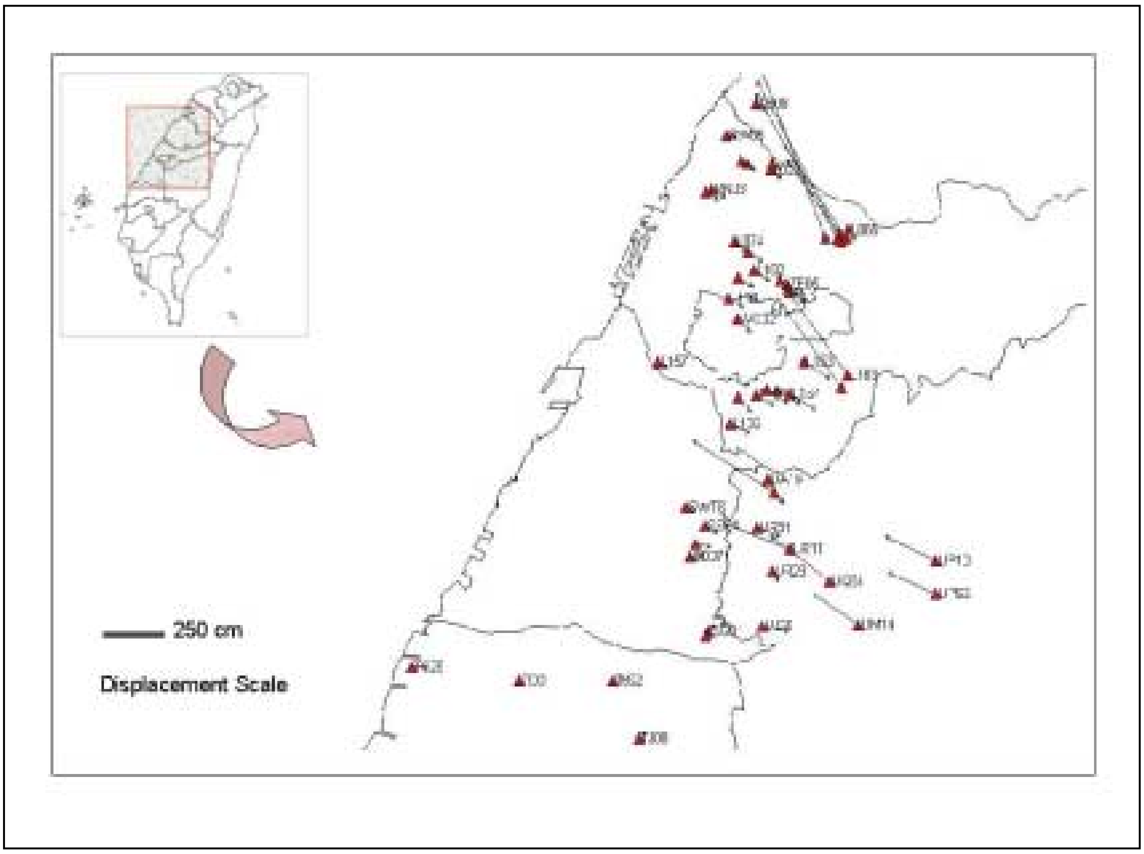

Fig. 4. Horizontal displacements estimated using GPS data

It is clear to see from Table 3 that the minimum horizontal displacement is still up to around 10 cm in the area rocked by the 1999 Chi-Chi earthquake, and most sites shown in Figure 4 are seen to move towards north-west direction. The displacement can be even up to 8.5 m in Taichung county, where is located at the northern end of Chelungpu fault. It can be also found from Figure 4 that more significant level of displacement occurred along the Chelungpu fault. Such obvious horizontal displacement, along with the vertical displacement of 1 - 8 m measured by the Central Geological Survey with levelling, has clearly indicated the fault trace ruptured at the earthquake (see Figure 5). It is, hence, believed that the data collected from the estimation of surface displacements and the investigation of geological structures would be helpful to realise more about a damaging earthquake.

Fig. 5. Fault trace ruptured at the earthquake
(photo provided by the Academia Sinica)

CONCLUSIONS

This paper has shown a significant level of horizontal displacement caused by the 1999 Chi-Chi earthquake in Central Taiwan, with the use of coordinate data measured by GPS. This earthquake is believed to have produced the largest surface displacement ever observed in this area. It also brings many opportunities for the surveyors to carry on their works. These include the interpretation of aerophotos and satellite images to understand the damages, the use of GPS to illustrate the trace of fault, the fieldwork of digital mapping to assist the urban and rural planning, and the re-survey of GPS control stations to support the cadastral survey. The complete data sets recorded on the earthquake and provided by the geodesists, seismologists, geologists, and earthquake engineers would be valuable for the people to fully understand any nature effects related to the damaging earthquake.

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