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ORIGINAL ARTICLE

An automatic scheme for baseline correction of strong-motion records in coseismic deformation determination

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Abstract Coseismic deformation can be determined from strong-motion records of large earthquakes. Iwan et al. (Bull Seismol Soc Am 75: 1225–1246, 1985) showed that baseline corrections are often required to obtain reliable coseismic deformation because baseline offsets lead to unrealistic permanent displacements. Boore (Bull Seismol Soc Am 91:1199–1211, 2001) demonstrated that different choices of time points for baseline correction can yield realistically looking displacements, but with variable amplitudes. The baseline correction procedure of Wu and Wu (J Seismol 11:159–170, 2007) improved upon Iwan et al. (Bull Seismol Soc Am 75:1225–1246, 1985) and achieved stable results. However, their time points for baseline correction were chosen by a recursive process with an artificial criterion. In this study, we follow the procedure of Wu and Wu (J Seismol 11:159–170, 2007) but use the ratio of energy distribution in accelerograms as the criterion to determine the time points of baseline correction automatically, thus avoiding the manual choice of time points and speeding up the estimation of coseismic deformation. We use the 1999 Chi-Chi earthquake in central Taiwan and the 2003 Chengkung and 2006 Taitung earthquakes in eastern Taiwan to illustrate this new approach. Comparison between the results from this and previous studies shows that our new procedure is suitable for quick and reliable determination of coseismic deformation from strong-motion records.

Keywords Taiwan · Baseline correction · Strong-motion record · Coseismic deformation

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1 Introduction

Taiwan is located in a plate boundary region with complex tectonic structures and high seismic activity. The Central Weather Bureau of Taiwan monitors the regional earthquake activity with a variety of instrumentation networks, among which the Taiwan Strong-Motion Instrumentation Program, in operation since 1991, provides a lot of strong-motion records of large earthquakes. These records contain important information for the investigation of the coseismic deformation and rupture processes of large earthquakes (Wu et al. 2006a, b). In general, coseismic deformation can be obtained from records of ground acceleration by a double integration in time (Boore 1999, 2001; Wu and Wu 2007). In reality, tilting of the ground, hysteresis phenomenon of the transducers, and/or problems in instrumental effects during strong shaking may cause shifts in the baselines of records. As a result, it may be rather difficult to estimate coseismic deformation directly from most of the strong-motion records. Thus, an empirical and approximate approach must be adopted.

Iwan et al. (1985) showed that the baseline shift is caused by the transducer hysteresis occurring when the ground acceleration exceeds about 50 cm/s^2. The correction for the baseline offset can be determined from the linear trend in velocity obtained by integrating the acceleration record in time. Boore (1999, 2001) showed that ground tilt is another source of baseline offset and applied corrections to the records of the 1999 Chi-Chi earthquake. Graizer (2005, 2006) also studied the impact of ground tilt in strong-motion records by numerical simulations and spectral analyses. All baseline correction schemes proposed in these studies showed wildly varying coseismic deformation. Wu and Wu (2007) improved upon Iwan et al. (1985) in computing coseismic deformations from strong-motion records of the 1999 Chi-Chi

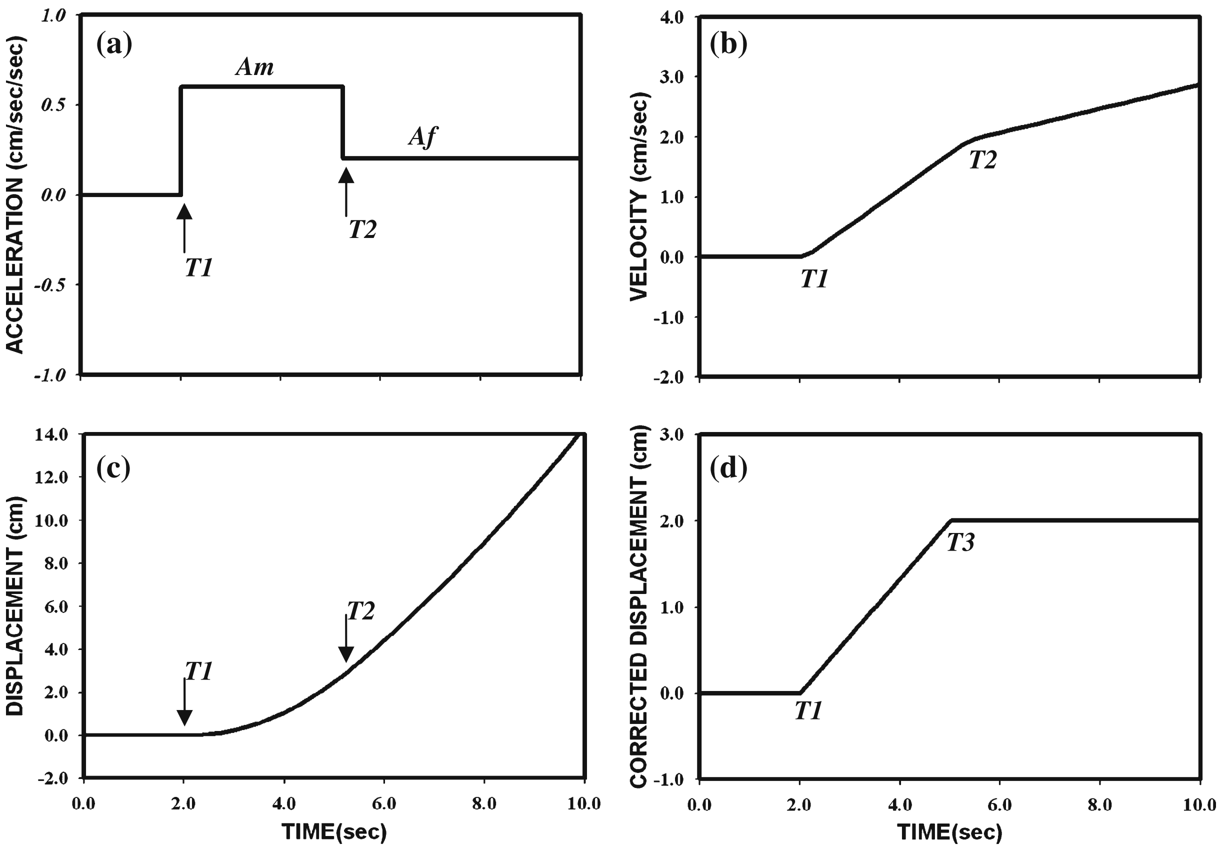

Fig. 1 (**a**), (**b**), and (**c**) show the procedure of Iwan et al. (1985) for baseline shift correction for acceleration, velocity, and displacement time histories, respectively. (**d**) A "well"-corrected displacement history has the shape of a ramp function. Wu and Wu (2007) proposed to choose T1 the point at which the ground starts to move to the permanent displacement position, and T3 the point when the ground has just moved into the permanent displacement position

(Mw = 7.6) and the 2003 Chengkung earthquake (Mw = 6.8), and compared their results with measurements from global positioning system (GPS).

The procedure proposed by Wu and Wu (2007) is already a standardized approach for baseline correction. However, the time points in their correction procedure are determined by artificial choices in a recursive process. Experiences from previous studies (Wu et al. 2006a, b; Wu and Wu 2007) suggest that the ratio of energy distribution in accelerograms could be used for determining the time points in baseline correction process. This property can be used to establish a more uniform criterion, which allows for an automatic, rapid, and routine procedure for determining coseismic deformations caused by large earthquakes.

2 Method

Procedures on how coseismic deformation can be recovered from strong-motion records have been proposed since 1976 (Bogdanov and Graizer 1976; Graizer 1979, 1989). Iwan et al. (1985) was the first one to propose the two-baseline offset correction. They assumed that the baseline of strong-motion records experiences a drift caused by the transducer hysteresis during strong shaking, resulting in two baseline offsets: A_m between times T1 and T2, and A_f from time T2 to the end of the record (Fig. 1a). They chose T1 as the time at which the absolute value of acceleration first exceeds 50 cm/s^2, and proposed two options for T2: (1) the time at which the absolute value of acceleration last exceeds 50 cm/s^2 or (2) the value chosen to minimize the final displacement. A least-squares fitting is then used to remove the linear trend from T2 to the end of the record in the velocity seismogram obtained by integrating the acceleration (Fig. 1b). This linear trend can be expressed as

$$V_f(t) = V_0 + A_f t. \tag{1}$$

Thus A_m can be determined by

$$A_m = \frac{V_f(\text{T2})}{(\text{T2} - \text{T1})}. \tag{2}$$

The baseline correction by removing A_m and A_f can avoid shift in displacement seismograms (Fig. 1c). Wu and Wu (2007) improved the method of Iwan et al. (1985) by introducing another time point, T3, and giving the physical meanings of the time points T1 and T3. They found that the

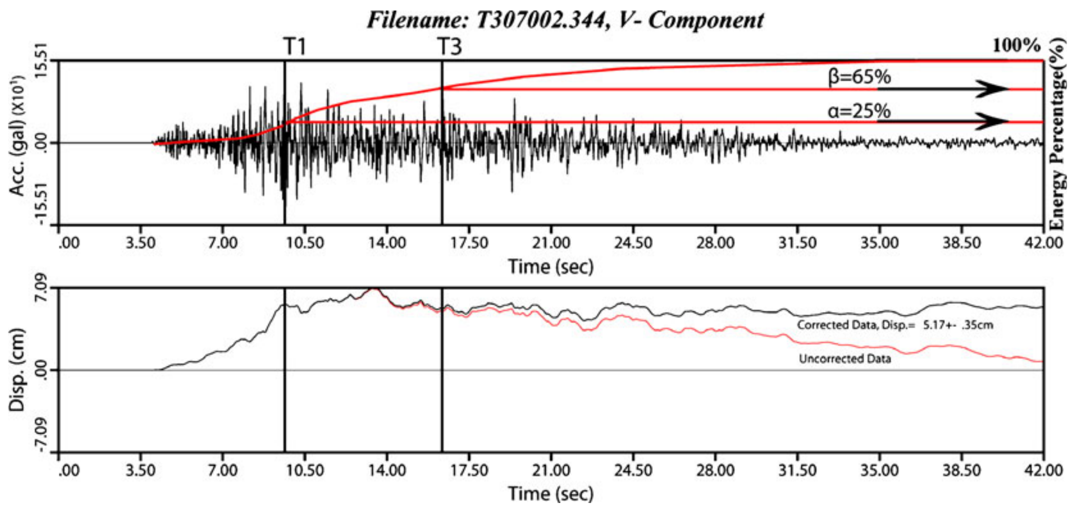

Fig. 2 Top plot shows the vertical-component accelerogram from the 2003 Chengkung earthquake at the station TTN033. The *red line* is the ratio of energy distribution in the accelerogram accumulated from the P-wave arrival time. Bottom plot shows the uncorrected (*red*) and corrected (*black*) displacements with a double integration in time from the accelerogram

corrected displacement seismogram takes the shape of a ramp function (Fig. 1d). They proposed that T1 should be chosen to be the time at which the ground starts to move from zero displacement. After the ground approaches the permanent displacement position, the corrected displacement waveform should be very flat (Wu et al. 2006a, b). Thus, they defined a correction time point T3 at which the ground has just moved to the permanent displacement position (Fig. 1d), and a flatness index, the f value, determined using the waveform from T3 to the end of the record. In this approach, they conducted baseline correction to the velocity record by taking as tentative T2 every time point from T3 to the end of the record. Then, the time point that leads to the maximum f value was chosen as the final T2. Thus, in this process, the T1 and T2 time points were determined by a recursive process, which prevented the coseismic deformation to be estimated automatically.

Further investigation suggested that the T1 and T3 time points may be located on certain values of ratio of energy distribution (E_r) in accelerograms. The ratio of energy distribution (E_r) in the accelerogram is defined as

$$E_r = \left(\sum_{i=n_p}^{n_c} \frac{a_i^2}{E_T} \right) \times 100\,(\%)\,, \quad E_T = \sum_{i=n_p}^{n_p+N} a_i^2 \qquad (3)$$

Table 1 Comparison of coseismic displacements of the 2003 Chengkung earthquake obtained in Wu and Wu (2007) and this study at 27 sites

Station	Lat.	Long.	Wu and Wu (2007)			This study		
	(N)	(E)	Up	North	East	Up	North	East
TTN014	23.099	121.365	12.300	9.400	6.600	14.281	11.503	5.060
TTN022	23.097	121.211	5.840	0.570	−1.040	5.940	2.625	1.350
TTN032	23.246	121.406	3.060	4.650	2.010	3.385	7.749	3.204
TTN020	23.127	121.206	4.700	1.000	3.080	4.610	3.505	2.899
HWA042	23.222	121.257	1.460	0.860	0.110	2.741	0.944	0.582
HWA041	23.267	121.294	2.360	3.050	1.040	2.583	3.341	0.777
TTN033	23.193	121.388	6.450	6.760	6.490	5.171	7.679	6.569
TTN024	22.972	121.108	−0.310	−0.620	0.030	3.927	−1.721	0.799
TTN025	22.904	121.072	−0.690	−1.970	0.400	3.496	−1.049	2.659
TTN047	22.840	121.131	2.430	−1.120	−2.050	3.682	−0.863	−2.604
TTN026	22.863	121.083	1.060	−1.780	−1.170	3.692	−2.541	1.375
TTN051	23.189	121.017	−0.150	−1.800	3.400	1.085	−1.333	4.209
TTN006	22.772	121.138	1.900	−3.920	−2.050	−0.722	−2.905	−0.789
TTN008	22.760	121.152	1.200	−0.940	−2.550	1.961	−1.264	−1.863
TTN007	22.765	121.143	1.720	−2.540	−1.220	1.006	0.861	−0.665
HWA037	23.454	121.384	0.010	2.230	0.040	−0.605	1.759	−0.050
TTN027	22.808	121.086	0.030	−0.660	−1.430	2.829	−0.667	0.184
TTN011	22.784	121.110	1.030	−2.170	−0.710	3.757	0.468	1.948
TTN018	22.821	121.072	0.290	−0.250	0.030	3.042	−1.527	0.290
TTN013	22.768	121.128	2.240	−1.620	−2.440	4.862	0.890	0.028
TTN015	22.754	121.146	2.470	−2.330	−0.660	2.225	−1.942	1.578
TTN005	22.757	121.140	1.800	−1.090	−2.370	1.531	0.677	−1.200
TTN048	22.773	121.083	1.060	−2.330	−1.270	1.470	−4.354	−3.714
TTN010	22.740	121.114	0.410	−1.220	0.050	2.183	−0.808	2.043
TTN028	22.779	121.054	0.600	−1.010	−0.140	2.225	−1.942	−1.578
TTN029	22.718	121.04	−0.060	−0.890	0.010	1.292	−2.112	3.631
TTN030	22.700	121.018	−0.580	−0.870	−0.480	−0.965	−1.802	−0.491

Displacement unit in centimeters

where n_p is the point of P-wave arrival time and n_c is the point corresponding to α or β. N is total number of points and a_i is the acceleration value of the ith point. Based on this physical explanation, T1 is the time at which the ground starts to move and must be located on the first 50% of the energy distribution in accelerograms. On the other hand, T3 will be located on the last 50% of the energy distribution in accelerograms. Thus, we can use the ratio of the energy distribution, α and β, in places of T1 and T3, respectively. Figure 2 shows the T1 and T3 time points and the corresponding α and β values. In this study, the α and β values are estimated from the accumulative energy distributions since the P-wave arrival time.

3 Data

We use strong-motion records from three recent large earthquakes in Taiwan to illustrate our automatic baseline correction procedure. The coseismic deformation of the 2003 Chengkung

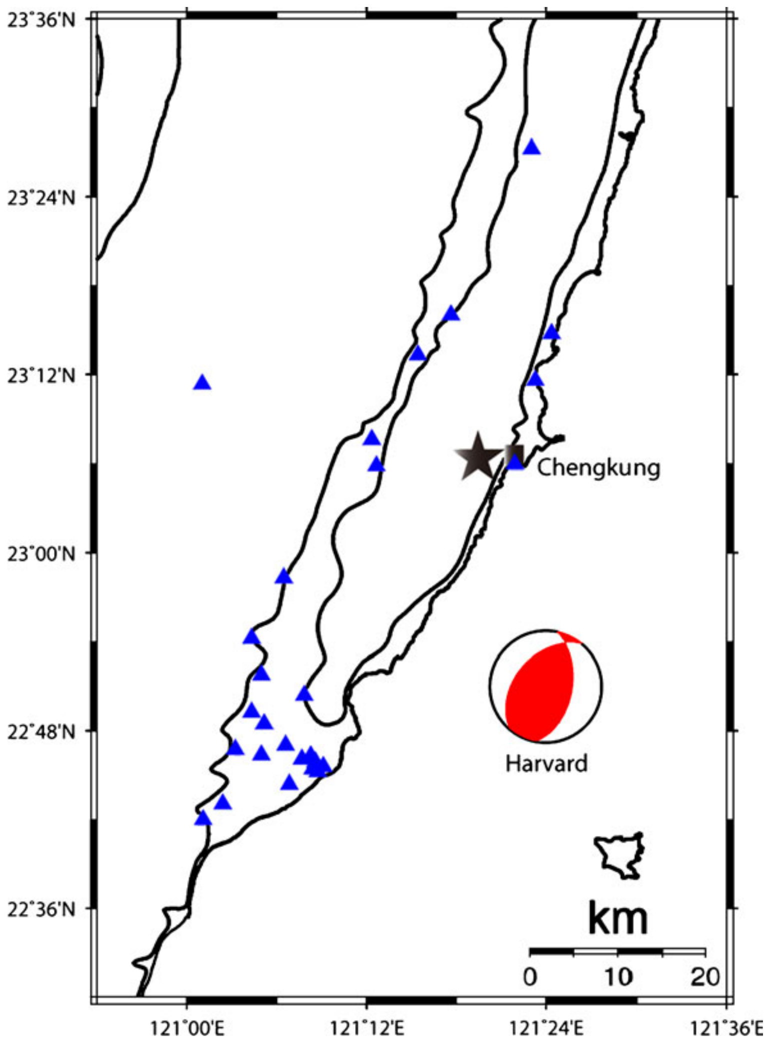

Fig. 3 Distribution of 27 strong-motion stations with A900A instruments (*blue triangles*). The Harvard CMT catalog shows that the 2003 Chengkung earthquake (*star* shows epicenter) is a thrust event. It occurred near the Chengkung township and was well recorded by the strong-motion stations

earthquake is well studied using the GPS and strong-motion records (Hu et al. 2007; Wu et al. 2006a; Wu and Wu 2007). Here, we use 27 strong-motion records (Table 1 and Fig. 3) from this earthquake in the optimization process for finding α and β thresholds, and the results from Wu and Wu (2007) will be used as a comparison. The accelerograms were recorded by A900A instruments. The A900A instruments are produced by Teledyne Geotech. They are digital accelerographs with recording range of ± 2 g, a sampling rate of 200 samples per second, and a 16-bit resolution. They had been subjected to shake-table tests before installation in the field. We also analyze 16 strong-motion records from the 2006 Taitung earthquake (Wu et al. 2006b) and ten large coseismic deformation strong-motion records from the 1999 Chi-Chi earthquake on the hanging wall (Wu and Wu 2007) to estimate the coseismic deformation using the optimized α and β values and compare them with results from previous studies.

4 Results

In this study, we use the coseismic deformation obtained in Wu and Wu (2007) as the reference for the 2003 Chengkung earthquake. Figure 4 shows the misfit contours of the coseismic deformations for different α and β values obtained by the automatic approach described in this study relative to that in Wu and Wu (2007). The values of contours represent the mean misfit of vertical and horizontal component records under the L1 norm. The result shows that the optimal α and β values are located at 25% and 65%, respectively. Figure 5 shows the coseismic deformations at the strong-motion stations corresponding to the optimal α and β values, which agree very well with the results of Wu and Wu (2007), especially at sites with relatively large coseismic deformation values. It is worth noting that the contour values in Fig. 4 change more closely with T3. This indicates that the coseismic deformation estimation is more sensitive to T3 than T1.

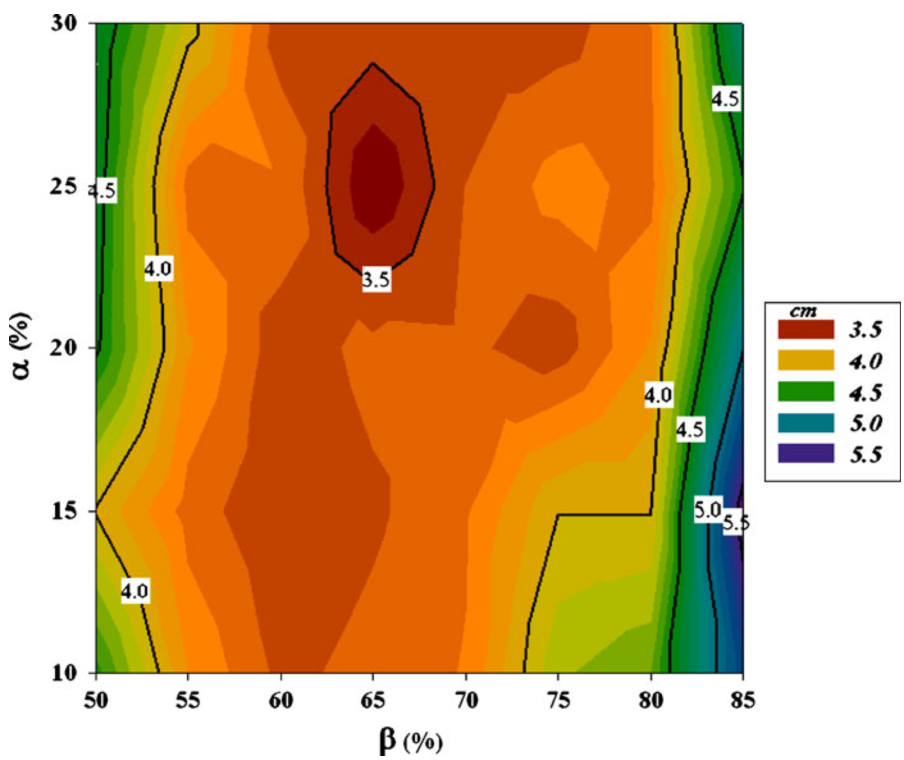

Fig. 4 Misfit contour between the coseismic deformations of the 2003 Chengkung earthquake obtained in Wu and Wu (2007) and in this study with different α and β values

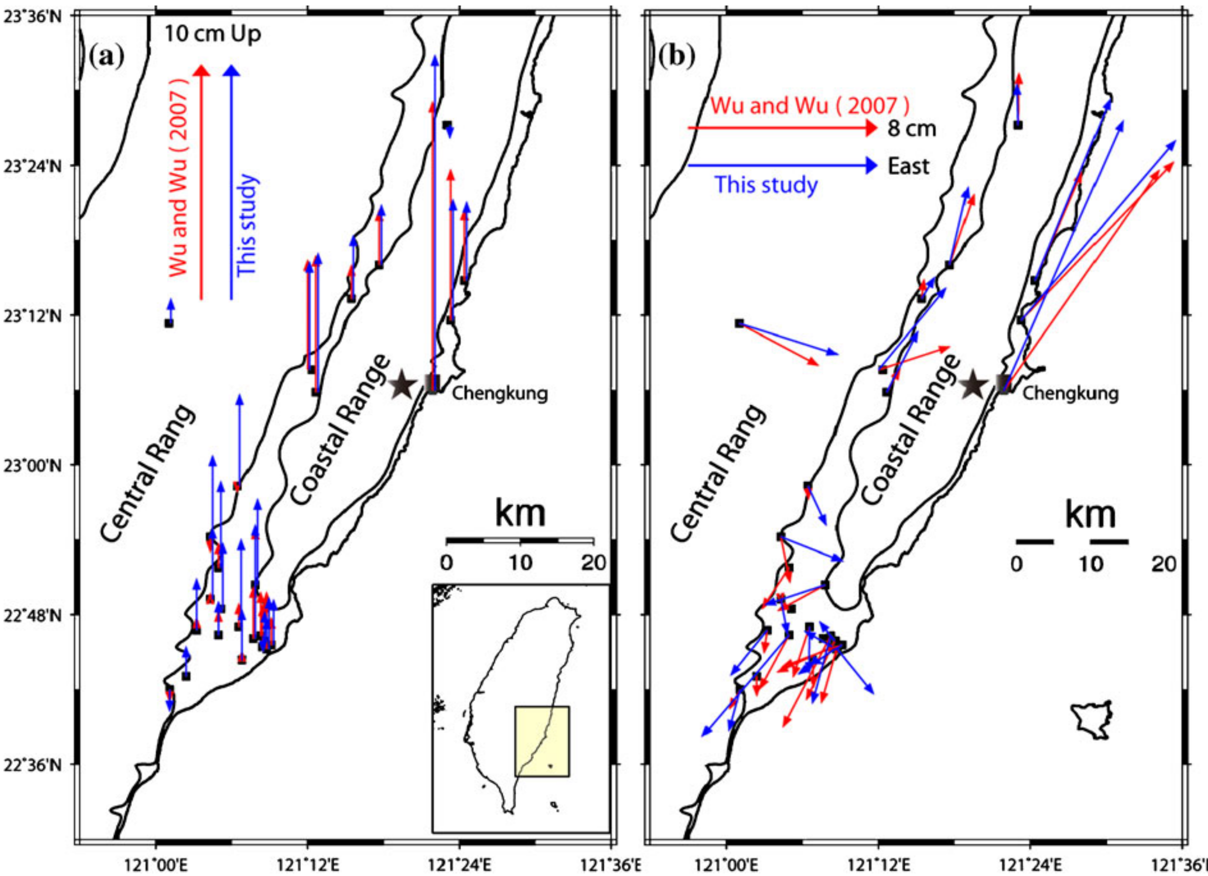

Fig. 5 Coseismic deformation of the 2003 Chengkung earthquake determined in Wu and Wu (2007) (*red vectors*) and this study (*blue vectors*). **a** Vertical component and **b** horizontal component. *Black star* indicates the epicenter of the earthquake

In order to further examine the effectiveness of our automatic baseline correction approach, we analyze the strong-motion records of the 2006 Taitung earthquake (Wu et al. 2006b), an event of much smaller coseismic deformation, and the 1999 Chi-Chi earthquake (Boore 1999, 2001; Yu et al. 2001), an event of large coseismic deformation. Figure 6 compares the coseismic deformations of the 2006 Taitung earthquake obtained in this study from 16 strong-motion records with the results of Wu et al. (2006b). The 2006 Taitung earthquake is a strike-slip event which resulted in relatively small coseismic deformations. Figure 6 shows that the results determined in this study by the automatic baseline correction procedure are consistent with those of Wu et al. (2006b). Unlike the strike-slip Taitung event, the 1999 Chi-Chi earthquake is a thrust event on an eastward-dipping fault plane (Chang et al. 2000, 2007). It produced large coseismic deformations on the hanging wall within the rupture area. Here, we use ten strong-motion records on the hanging wall with epicentral distances less than 60 km and coseismic deformations large than 1 m as determined in Wu and Wu (2007) to examine our automatic baseline correction approach for records of large shaking. In Fig. 7, the coseismic deformations on the hanging wall of the Chi-Chi earthquake obtained by the automatic procedure are compared with the results of Wu and Wu

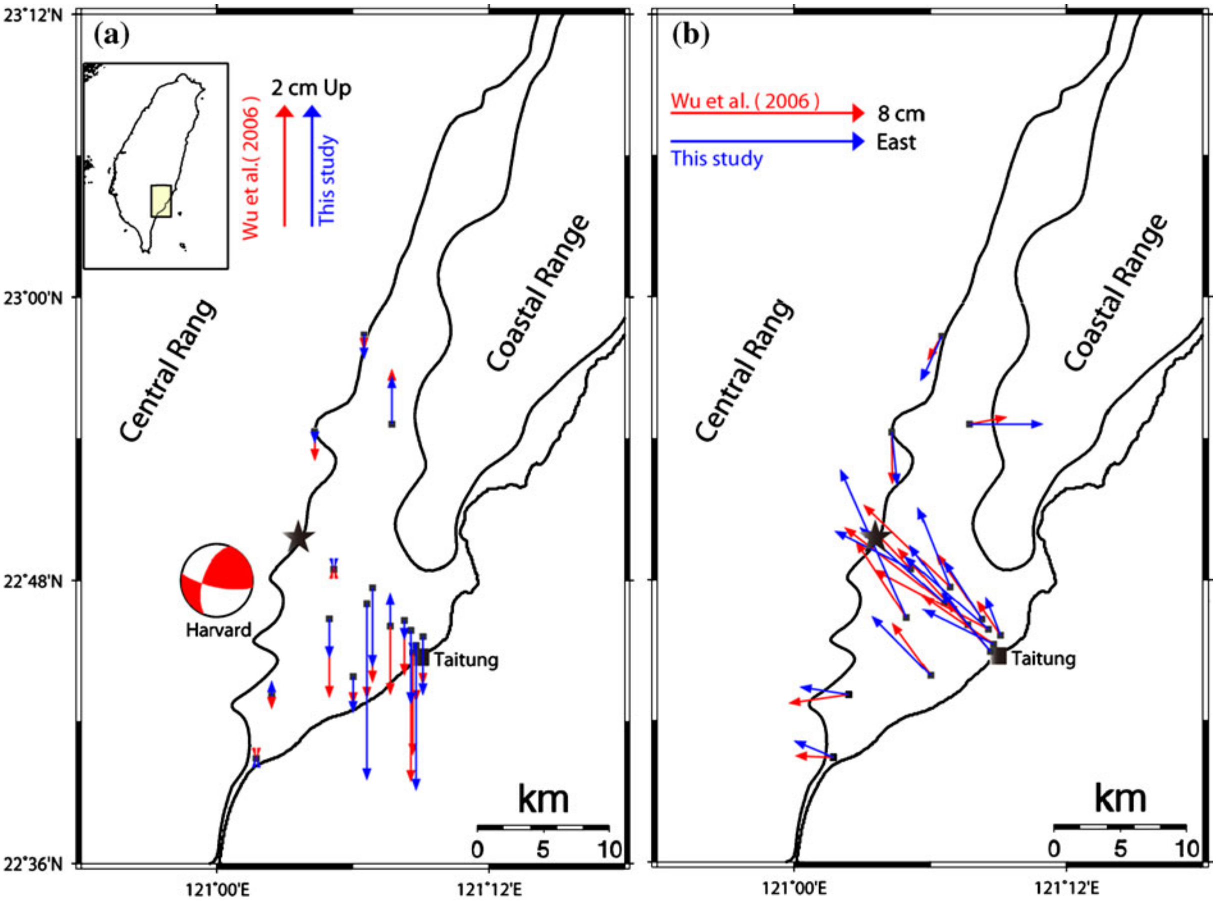

Fig. 6 Coseismic deformation of the 2006 Taitung earthquake determined in Wu and Wu (2007) (*red vectors*) and this study (*blue vectors*). **a** Vertical component and **b** horizontal component. *Black star* indicates the epicenter of the earthquake

(2007). It can be seen clearly from the horizontal component that the hanging-wall block moved in a northwestward direction, and the two results are consistent. Based on the comparisons for the coseismic deformation results from these two events, we conclude that our automatic procedure for baseline correction works for both large and small coseismic deformation records.

5 Discussion and conclusions

Wu and Wu (2007) suggested that the time point T1 in baseline correction should be the point in the record at which the ground starts to move from zero displacement. In this study, however, we determined T1 to be at $\alpha = 25$ %. In general, our T1 is at a place after the point when the ground starts to move from zero displacement, and is about 3–5 s before the time of peak-ground displacement. Our results show that the final coseismic deformation is more sensitive to the T3 point than T1, which may be one of the reasons for the difference in the T1 values.

In addition to the ratio of energy distribution criterion we adopted in this study, we have also experimented with other constraints in the determination of T1 and T3, such as the acceleration threshold (Iwan et al. 1985) for finding T1 and T3, and a combination of the acceleration threshold and the ratio of energy distribution. Results show that our current approach has the best perfor-

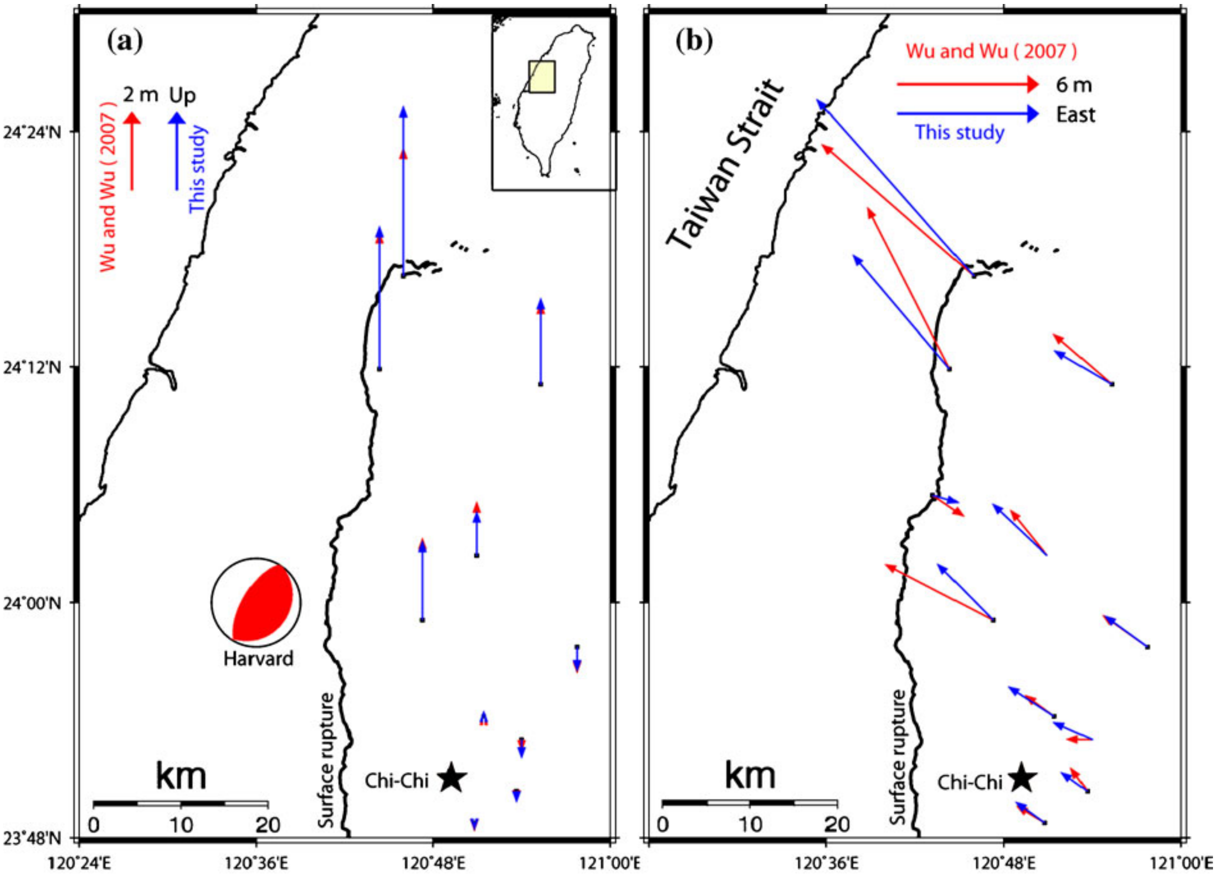

Fig. 7 Coseismic deformation of the 1999 Chi-Chi earthquake determined in Wu and Wu (2007) (*red vectors*) and this study (*blue vectors*). **a** Vertical component and **b** horizontal component. *Black star* and *red lines* indicate the epicenter and surface ruptures, respectively, of the 1999 Chi-Chi earthquake

mance. The acceleration threshold does not yield good results.

Based on results in this study, we conclude that it is an effective way to use the ratio of energy distribution as the threshold to determine the time points T1 and T3 in baseline correction for coseismic deformation estimation. Our tests show that the result is more sensitive to T3 than T1. This approach works for both small and large coseismic deformation strong-motion records, although records of very small coseismic deformations may lead to relatively poor results due to their lower weights in the fitting process and their relatively poor signal-to-noise ratio. In the Chengkung earthquake case, the coseismic deformations in the southern area are relatively small than in the northern area. This is the reason that the fitness in the southern portion is poorer than in the northern portion. In addition, coseismic deformations are generally recorded by the low frequency portions of the records. Thus, instruments with poor performance at longer periods may not be suitable for such analysis, such as the instrument A800 produced by Teledyne Geotech. However, this automatic baseline correction procedure allows us to determine the coseismic deformation in a rapid and real-time manner. Most of the modern seismic networks are now equipped with strong-motion sensors. With our automatic approach, we will be able to determine the coseismic deformation immediately following the occurrence of a large earthquake and facilitate the calculation of a shake map and the rapid assessment of seismic hazard.

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References

Bogdanov VE, Graizer VM (1976) The determination of the residual displacement of the ground from the seismogram. Rep Acad Sci USSR 229:59–62

Boore DM (1999) Effect of baseline corrections on response spectra for two recordings of the 1999 Chi-Chi, Taiwan, earthquake. US Geol Surv Open-File Rept 99–545, p 37

Boore DM (2001) Effect of baseline corrections on displacements and response spectra for several recording of the 1999 Chi-Chi, Taiwan, earthquake. Bull Seismol Soc Am 91:1199–1211

Chang CH, Wu YM, Shin TC, Wang CY (2000) Relocating the 1999 Chi-Chi Earthquake, Taiwan. Terr Atmos Ocean Sci 11:581–590

Chang CH, Wu YM, Zhao L, Wu FT (2007) Aftershocks of the 1999 Chi-Chi, Taiwan, earthquake: the first hour. Bull Seismol Soc Am 97:1245–1258

Graizer BM (1989) On inertial seismometry. Izv Earth Phys 25:26–29

Graizer VM (1979) Determination of the true ground displacement by using strong motion records. Izv Earth Phys 25:26–29

Graizer VM (2005) Effect of tilt on strong motion data processing. Soil Dyn Earthqu Eng 25:197–204

Graizer VM (2006) Tilts in strong ground motion. Bull Seismol Soc Am 96:2090–2102

Hu JC, Cheng LW, Chen HY, Wu YM, Lee JC, Chen YG, Lin KC, Rau RJ, Kuochen H, Chen HH, Yu SB, Angelier J (2007) Coseismic deformation revealed by inversion of strong motion and GPS data: the 2003 Chengkung earthquake in eastern Taiwan. Geophys J Int 169:667–674. doi:10.1111/j.1365-246X.2007.03359.x

Iwan WD, Moser MA, Peng CY (1985) Some observations on strong-motion earthquake measurement using a digital acceleration. Bull Seismol Soc Am 75:1225–1246

Wu YM, Wu CF (2007) Approximate recovery of coseismic deformation from Taiwan strong-motion records. J Seismol 11:159–170

Wu YM, Chen YG, Shin TC, Kuochen H, Hou CS, Hu JC, Chang CH, Wu CF, Teng TL (2006a) Coseismic versus interseismic ground deformations, fault rupture inversion and segmentation revealed by 2003 Mw 6.8 Chengkung earthquake in eastern Taiwan. Geophys Res Lett 33:L02312. doi:10.1029/2005GL024711

Wu YM, Chen YG, Chang CH, Chung LH, Teng TL, Wu FT, Wu CF (2006b) Seismogenic structure in a tectonic suture zone: with new constraints from 2006 Mw 6.1 Taitung earthquake. Geophys Res Lett 33:L22305. 10.1029/2006GL027572

Yu SB, Kuo LC, Hsu YR, Su HH, Liu CC, Hou CS, Lee JF, Lai TC, Liu CL (2001) Preseismic deformation and coseismic displacements associated with the 1999 Chi-Chi, Taiwan, earthquake. Bull Seismol Soc Am 91:995–1012