Approximate recovery of coseismic deformation from Taiwan strong-motion records

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Abstract Since 1990, digital strong-motion accelerographs and global positioning system (GPS) instruments have been widely deployed in the Taiwan region (Shin et al. 2003; Yu et al. 2001). The 1999 Chi-Chi, Mw 7.6 earthquake and the 2003 Chengkung, Mw 6.8 earthquake were well recorded by both digital accelerographs and GPS instruments. These data offer a good opportunity to determine coseismic displacements from strong-motion records and to compare the results with those derived from GPS measurements. As noted by Boore (2001), a double integration of the acceleration data often leads to unreasonable results, and baseline corrections are therefore required in most cases before the integration. Based on the works of Iwan et al. (1985) and Boore (2001), we developed an improved method for baseline correction and validated it using an extensive set of data from shake-table tests of a known "step" displacement on 249 accelerographs. Our baseline correction method recovered about 97% of the actual displacement from the shake-table data. We then applied this baseline correction method to compute coseismic displacements from the strong-motion data of the Chi-Chi and Chengkung earthquakes. Our results agree favorably with the coseismic displacements determined by the GPS measurements at nearby sites. The ratio of seismic to geodetic displacement varies from 0.78 to 1.41, with an average of about 1.05.

1 Introduction

In 1991, the Central Weather Bureau (CWB) of Taiwan undertook a 6-year Taiwan Strong-Motion Instrumentation Program (TSMIP) to deploy over 600 digital accelerographs on free-field sites and an equivalent number of accelerographs in buildings and on bridges (Shin et al. 2003). With a station spacing of a few kilometers (except in unpopulated high-mountain areas), all felt earthquakes in Taiwan have been well recorded by the TSMIP network. In particular, the 1999 Chi-Chi earthquake (Mw=7.6) in central Taiwan was the best-recorded major earthquake in the 20th century, and the data were quickly released by the CWB (Lee et al. 1999, 2001).

The frequency response of a digital accelerograph is nominally flat in translational acceleration from DC to about 50 Hz. If there is no coseismic deformation at the accelerograph site and if the background and instrumental noises are low, the time histories of

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velocity and displacement during an earthquake can be recovered from the integrations of the acceleration data (with a DC correction by removing the mean determined from the pre-event segment of the record). However, if coseismic deformation occurs at the accelerograph site, an appropriate baseline correction is needed; otherwise, unreasonable displacements may result (Boore 2001; Boore et al. 2002). On the other hand, if six components of strong motion (three translational and three rotational) are recorded (Graizer 1989, 2005; Niggbor 1994; Trifunac and Todorovska 2001), the coseismic deformation can be precisely calculated. Currently, most of the strong-motion instruments are only the three translational components. Thus, anempirical and approximate approach must be considered.

Discussions on how coseismic deformation can be recovered from strong-motion record have been published since 1976 (Bogdanov and Graizer 1976; Graizer 1979, 1989). Methods of baseline correction to digital strong-motion records have been proposed later, for example, by Iwan et al. (1985) and Chiu (1997). In Chiu's method, the strong-motion data are first high-pass-filtered before integration. Thus, it can recover some but not all of the permanent displacement occurred, and his method is more appropriate for earthquake engineering purposes. The method of Iwan et al. (1985) appears to recover the permanent displacement, but the time points of the baseline corrections in Iwan et al. (1985) may not be where they are assumed to be, as pointed out by Boore (2001). In particular, Boore (2001) showed that various reasonable baseline correction schemes can lead to wildly different final displacements using the strong-motion records from the 1999 Chi-Chi earthquake.

The strong-motion records of the 1999 Chi-Chi main shock (Mw=7.6) have been used to estimate coseismic deformation by many authors (e.g., Boore 2001; Chung and Shin 1999), suggesting a coseismic deformation of up to about 7 m. However, there is not a standard procedure for baseline correction in processing strong-motion records in general. In this paper, we develop an improved method for baseline correction and validate it using an extensive set of data from shake-table tests of a known "step" displacement on 249 accelerographs. We then apply this baseline correction method to compute coseismic deformation from the strong-motion data of the 1999 Chi-Chi and 2003 Chengkung earthquakes.

2 An improved method for baseline correction

Iwan et al. (1985) attributed the source of the baseline shift to a hysteresis in the transducer that occurs when acceleration exceeds about 50 cm/s². Consequently, the baseline shift could change in a complicated way during the strongest shaking interval, and the baseline offset after the strong shaking
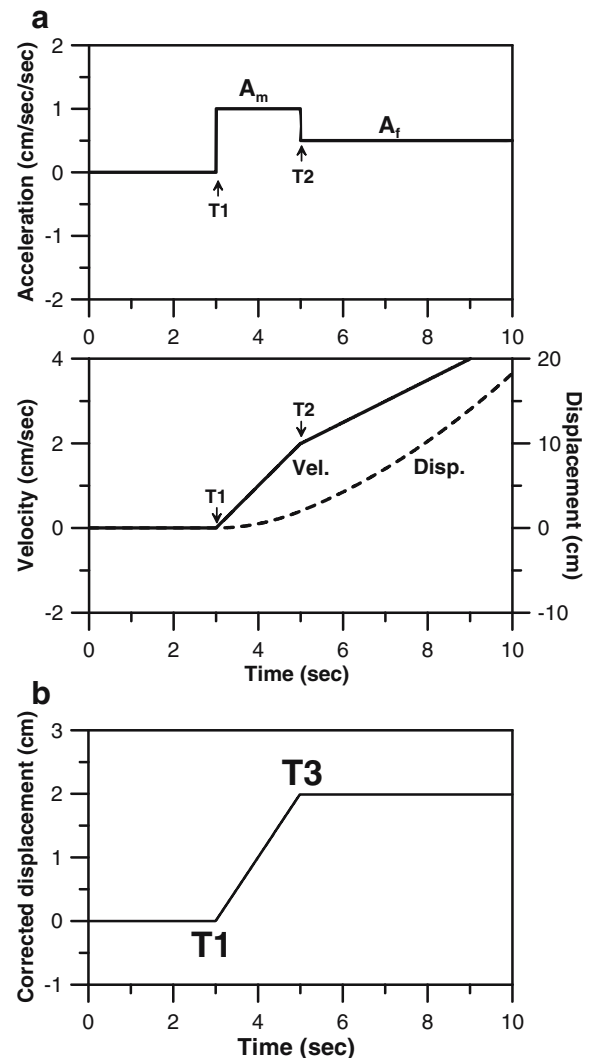

Fig. 1 (a) Iwan et al. (1985) baseline correction scheme from acceleration (top) to velocity and displacement (bottom). (b) A "good" corrected displacement history is similar to the ramp function. We propose to choose T1 the point at which the ground starts to move to the permanent displacement position, and T3 the point when the ground has just moved to the permanent displacement position

Fig. 2 Top: Observed acceleration for the east–west component at station TTN014 from December 10, 2003 (Mw6.8) earthquake. Middle: Velocities integrated from uncorrected (red) and corrected (black) accelerations. Bottom: Displacements for the uncorrected (red) and corrected (black) cases. After baseline corrections and double integration, 9.4 cm of permanent eastward displacement was obtained. At an almost co-site GPS station, a 9.3-cm eastward displacement was observed. Vertical lines mark T1, T2, and T3 show the correction time points. The thick red line plotted in the velocity record shows the correction baseline
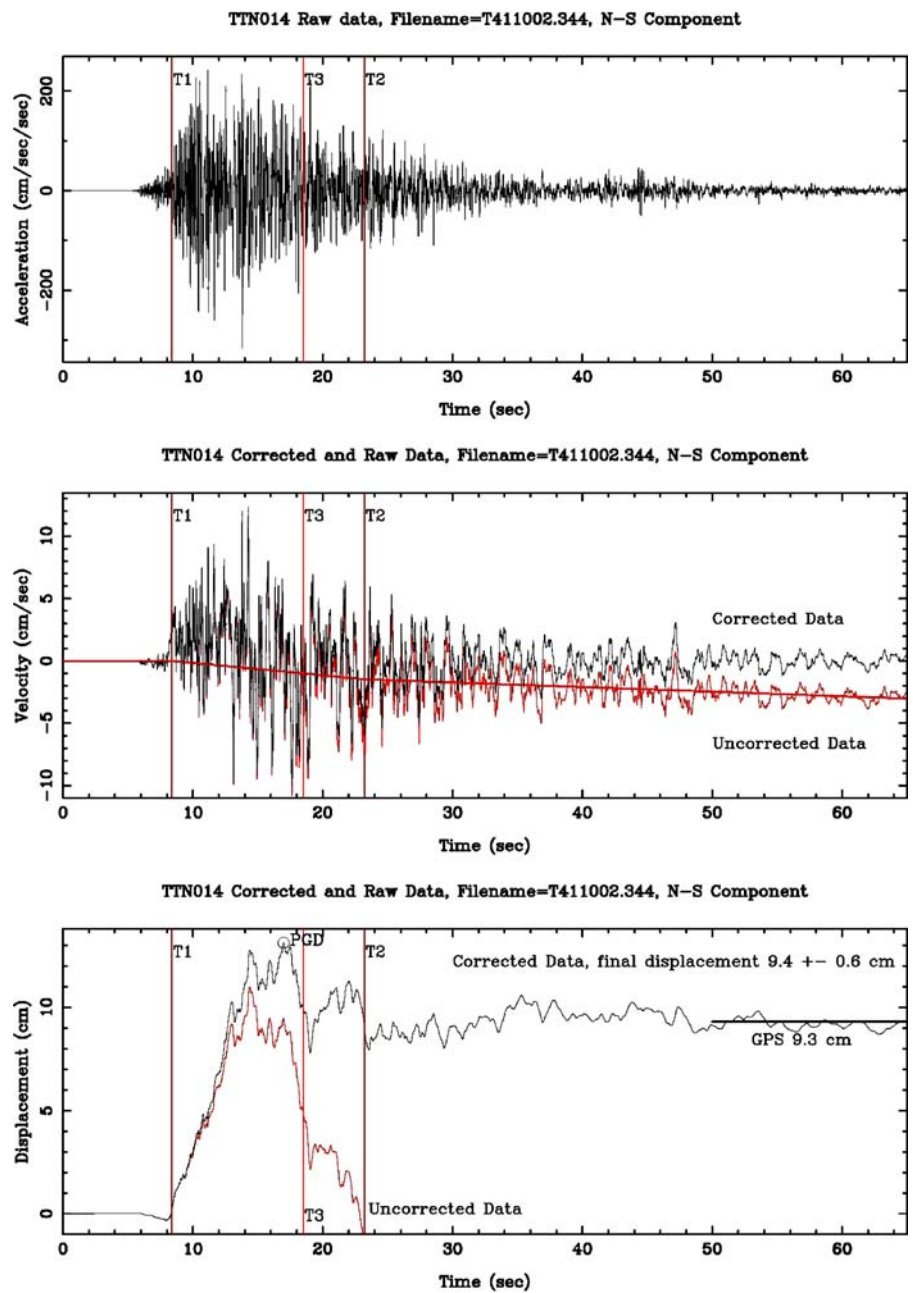
may be different from that before the strong shaking. Iwan et al. (1985) then proposed that two baseline offsets be removed: A_m between times T1 and T2, where T1 and T2 are the start and end times of the strongest shaking interval, respectively, and A_f from time T2 to the end of the record (Fig. 1a). The value A_m is an average of the complicated shifts in baseline that occur during the strong shaking. The level A_f is

determined from the slope of a linear fit to a portion of the velocity trace following the strong shaking:

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

In practice, the V_f line is found by a least-squares fit of the portion of the velocity from T2 to end of the

record. The correction A_m can be determined (Boore 2001) by

$$A_m = \frac{V_f(T2)}{(T2 - T1)} \qquad (2)$$

Boore (2001) suggested that hysteresis may be just one of the reasons causing baseline offsets, and that tilting of the ground must also be considered. We note that many of the velocities derived from uncorrected acceleration records from Taiwan show an approximately linear trend at long times. These records were taken either in near sources regions of large earthquakes (Chung and Shin 1999; Wu et al. 2006a, b) or very close to the epicenters of smaller earthquakes that may have localized coseismic deformations. Boore et al. (2002) further pointed out that there may be numerous other sources of offsets (e.g., hysteresis in the sensor, static buildup in the A/D converter, or tilting of the ground).

Based on the strong-motion records from TSMIP station and laboratory tests, we also obtained the baseline offset in Fig. 1a. This suggests that the method of Iwan et al. (1985) can provide a useful approximation, but that it is necessary to clearly define the T1 and T2 time points, as pointed out in Boore (2001). Iwan et al. (1985) chose T1 as the time that the absolute value of acceleration first exceeds 50 cm/s^2, and proposed two specific options for T2: (1) the time after which the acceleration never exceeds 50 cm/s^2; and (2) the value that minimizes the final displacement. However, using the correction of Iwan et al. (1985) does not lead to satisfactory results for the 1999 Chi-Chi earthquake, as noted in Boore (2001). Consequently, Boore (2001) suggested that T1 be made a free parameter and not determined by a threshold of shaking, and that T2 can take any value between T1 and the end of the record so long as the average corrected velocity is zero near the end of the record. However, with T1 being a free parameter, a wide range of final displacements may be obtained.

Generally, T1 should be chosen to be the point in the record where the ground starts to move from zero displacement. However, such a point is not always clear on the records, and it is also not necessarily the time at which the acceleration exceeds 50 cm/s^2.

Based on the results of Boore (2001) and our experience in processing strong-motion data with coseismic deformation (Wu et al. 2006a,b), we found that the corrected displacement history takes the shape of a ramp function (Fig. 1b). We therefore propose that T1 should be chosen to be the time at which the ground starts to move from zero displacement. If the T1 so determined is earlier than the time at which the absolute value of the acceleration first exceeds 50 cm/s^2 (i.e. T1 in Iwan et al. 1985), then we will select Iwan et al.'s T1 point.

After the ground moves to the permanent displacement position, the corrected displacement history should be very flat (Wu et al. 2006a,b). Thus, we define a correction time point T3 at which the ground has just moved to the permanent displacement position (Fig. 1b), and an *f*-value was determined using the waveform from T3 to the end of the record.
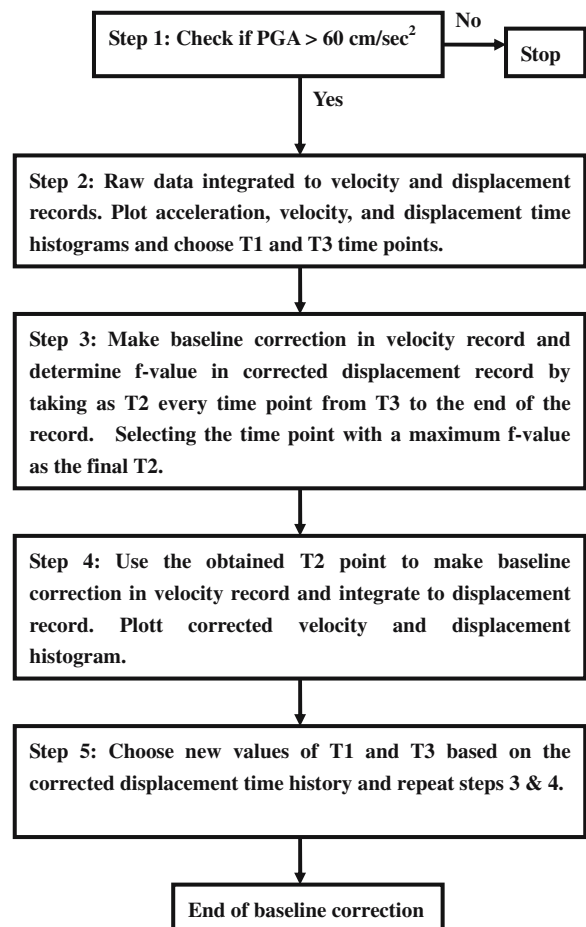

Fig. 3 Flow chart showing our baseline correction procedures

The *f*-value is a "flatness" indicator obtained from the corrected displacement history and is defined as

$$f = \frac{|r|}{|b| \cdot \sigma} \qquad (3)$$

where r is the linear correlation coefficient and b is the slope of the least-squares regression line of the corrected displacement history from T3 to the end of the record. We regard the mean value of the corrected displacement history from T3 to the end of the record as the "permanent displacement" and determine its variance σ. For a "good" strong-motion record, the displacement history should be very flat after T3. Thus, the absolute value of r should be very close to 1, b should be close to 0, and σ is at a minimum value. Under this condition, the *f*-value reaches to a maximum.

Fig. 4 Top: Observed acceleration for the north–south component of an A900 accelerograph (serial number 076) from a shake-table "step" test. Middle: Velocities integrated from uncorrected (red) and corrected (black) accelerations. Bottom: Displacements for the uncorrected (red) and uncorrected (black) cases. After baseline corrections and double integration, about 0.3-cm permanent displacement was obtained. Vertical lines marked by T1, T2, and T3 indicate the correction time points
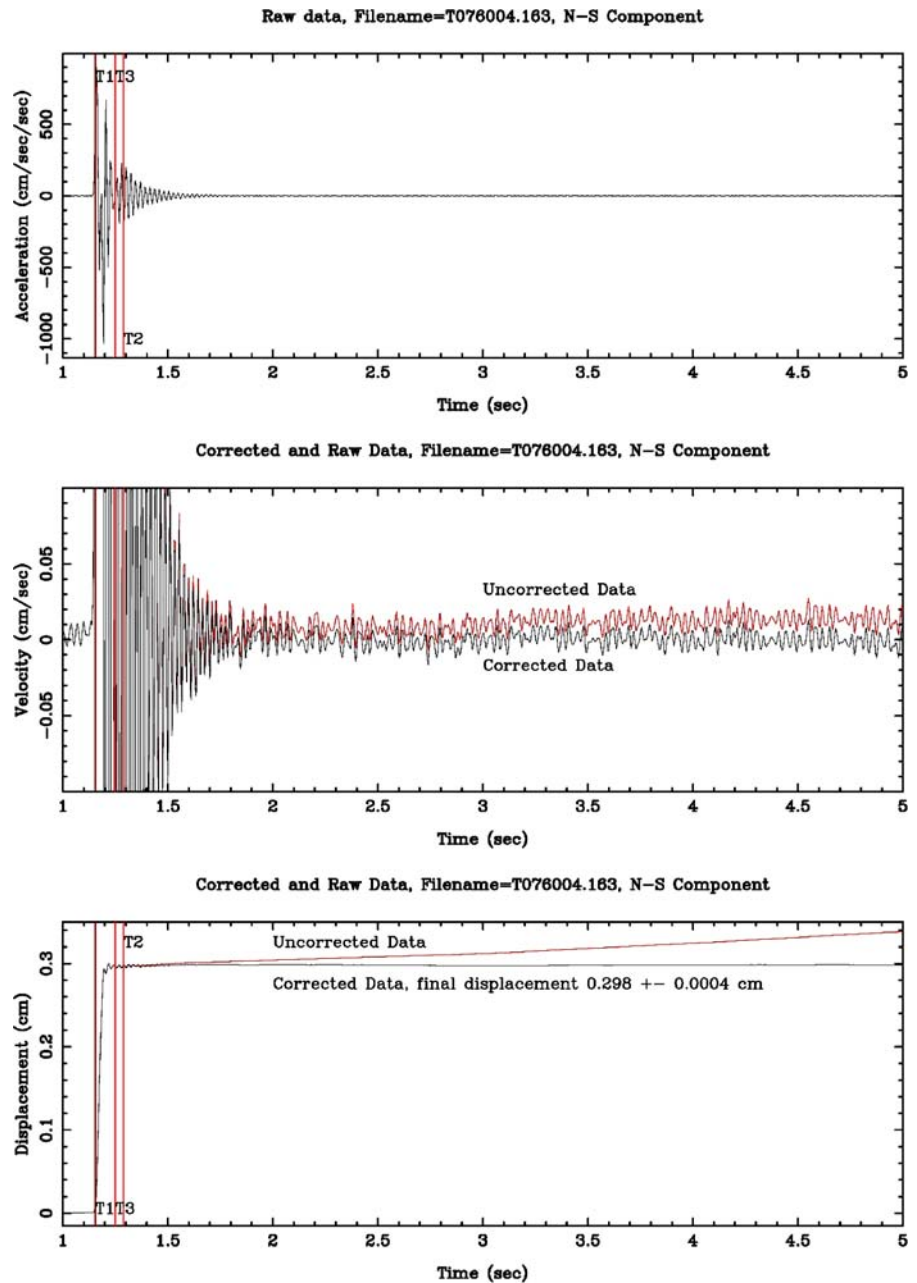
For T2, we defined it to be the value between T3 and the end of the record such that the *f*-value determined from the corrected displacement history is a maximum. We conduct baseline correction to the velocity record as mentioned above by taking as tentative T2 every time point from T3 to the end of the record. Then, we select the time point that gives the maximum *f*-value as the final T2. We use a least-squares fit to the portion of the velocity record from T2 to end of the record to determine the V_f line and the A_m value.

Figure 2 shows the corrected and raw data of a strong-motion record. Vertical lines marked by T1, T2, and T3 show the time points for baseline corrections. Because the T1 and T3 points are estimated by inspecting the integration results, two or more steps in baseline corrections are necessary in our method. Figure 3 is a schematic diagram of our procedures.

3 Data from shake-table tests

Most of the TSMIP instruments have been subjected to shake-table tests before installation in the field (CWB Instrumentation Committee 1994). The most important test is by using a series of "steps" (square waves with slightly rounded corners) as the input signal to the shake table. Displacements of 0.3-cm "steps" are generated on the shake table and recorded by the accelerograph. An accelerograph passes this test if the displacement obtained from double integration of the recorded acceleration is within ±10% of 0.3 cm. We collected 249 strong-motion records of the shake-table tests conducted about 10 years ago. The tested strong-motion instruments were the Teledyne Geotech Model A900 accelerograph with ±2 g full-scale, a 16-bit resolution, and a sampling rate of 200 samples per second. Most of those instruments are still in operation today, and they provided the majority of the strong-motion records of the 1999 Chi-Chi earthquake.

We applied our baseline correction method to this extensive dataset of shake-table "step" test. Figure 4 displays the corrected and uncorrected data recorded by an A900 instrument (serial number 076). This instrument is installed at the TSMIP station TCU068. It recorded the Chi-Chi main shock at a distance of 380 m from the fault surface rupture, where a peak

ground displacement of about 10 m was observed (Boore 2001; Chung and Shin 1999).

Figure 4 shows that the shake-table test produced a peak amplitude of about 1 g. The record has a very small offset in acceleration, and a linear trend can be seen in the integrated velocity history. After a double integration using our baseline correction method, we obtained a displacement of 0.298 cm, in good agreement with the input of 0.3-cm "step" to the shake table.

Figure 5a shows the results of the 249 accelerographs (Model A900) under the "step" tests, yielding a mean displacement of 0.300 cm with a standard deviation of 0.009 cm. Figure 5b shows the acceleration offset after the 0.3-cm displacement shaking. Most of the instruments caused only very small offsets with a mean acceleration of -0.002 cm/s^2 and a standard deviation of 0.027 cm/s^2. Generally, the offsets are less than one digital count (one count= 0.0598 cm/s^2). Hence, the A900 accelerographs can record the displacement in shake-table tests.
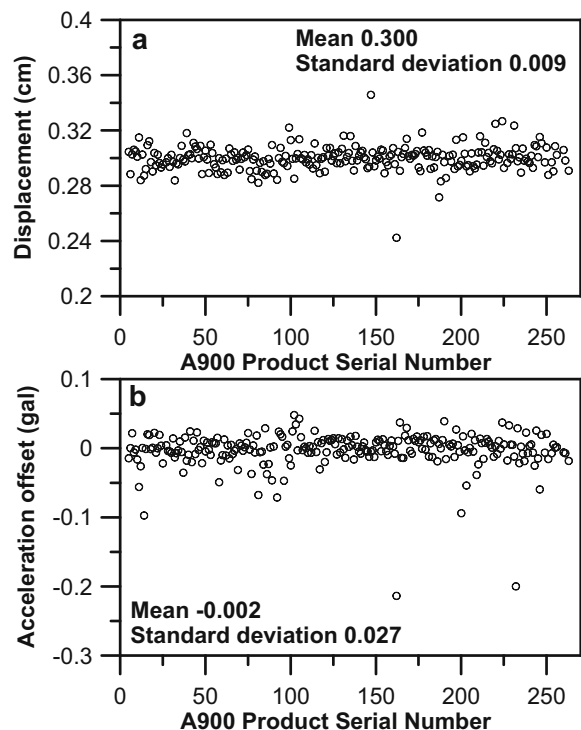

Fig. 5 (**a**) Permanent displacements obtained by 249 accelerographs from shake-table "step" tests plotted with their serial numbers. (**b**) Acceleration offsets after a 0.3-cm "step" shaking plotted with their serial numbers (most of the instrument offsets are less than one count)

4 Comparing displacements from strong-motion records with nearby GPS observations

Global positioning system (GPS) observations of coseismic deformations have been reported for the 1999 Chi-Chi, Mw 7.6 earthquake (Yu et al. 2001) and the 2003 Chengkung, Mw 6.8 earthquake (Chen et al. 2006). These two events were well recorded by the TSMIP instruments. Thus, they offer a good opportunity to examine the performance of our baseline correction method in recovering coseismic deformation.

We selected 16 strong-motion records (Table 1) for analysis. The selection criterion is based on data availability: distance between the strong-motion

Table 1 Comparison of coseismic deformation determined from strong-motion data with GPS measurements at 16 stations

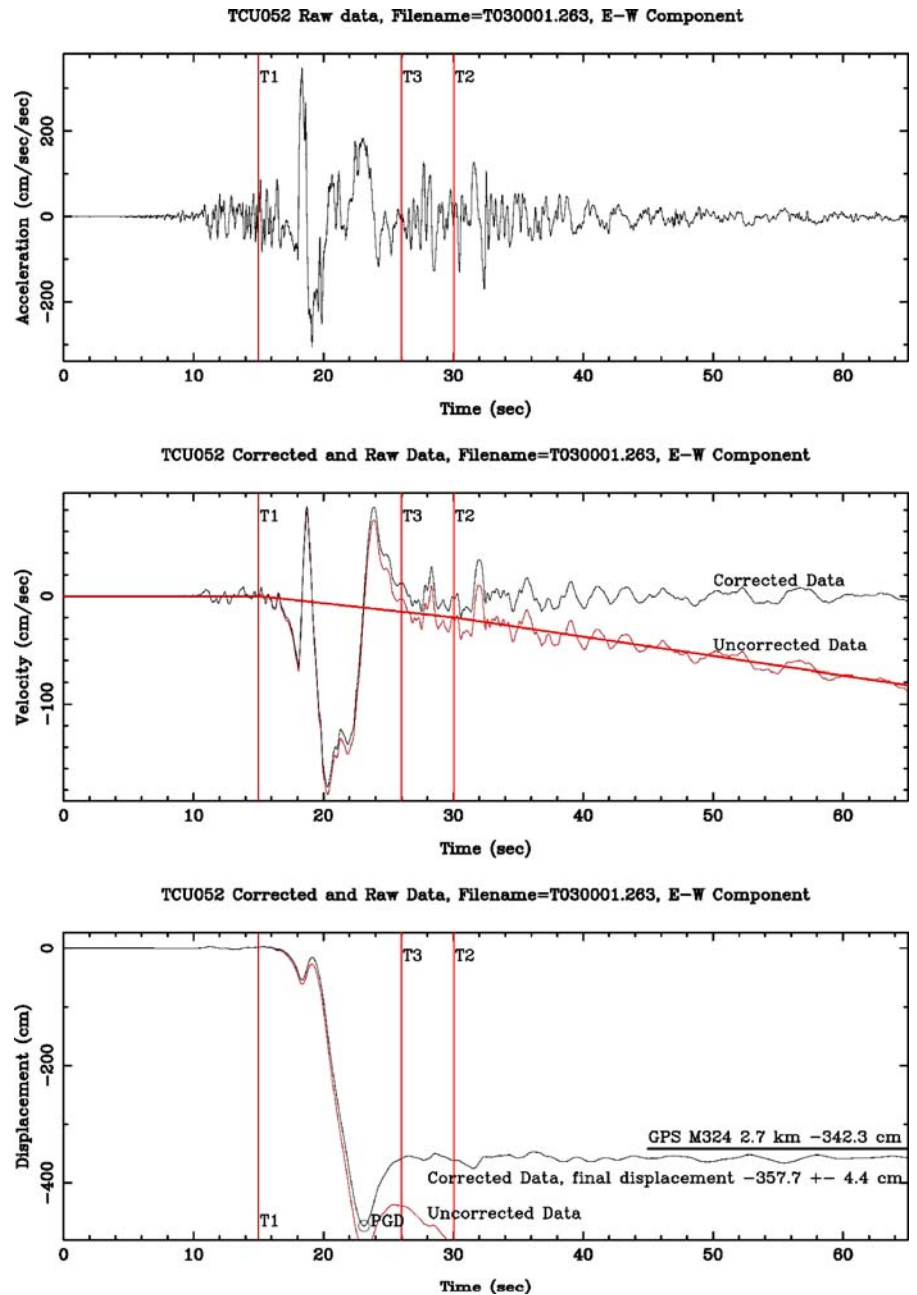| Strong motion observation				GPS					Distance (m)	Event
Code; filename; location	Displacement (cm); vertical–northeast			Code; location	Displacement (cm), vertical–northeast			Data source		
TTN014; T411002.344; 23.099°N, 121.365°E	12.3	9.4	6.6	CHEN; 23.099°N, 121.365°E	15.4	9.3	8.5	A	40	2003/12/10, Mw 6.8
TTN051; T301001.344; 23.187°N, 121.017°E	[a]	−1.8	3.4	MOTN; 23.202°N, 121.018°E	1.2	−1.5	3.1	A	1,430	2003/12/10, Mw 6.8
TTN001; 11934401.CVA; 23.318°N, 121.442°E	[a]	3.7	2.6	PING; 23.321°N, 121.446°E	4.0	3.1	1.2	A	525	2003/12/10, Mw 6.8
TTN020; T393001.344; 23.127°N, 121.206°E	4.7	1.3[b]	1.0[b]	TAPE; 23.127°N, 121.222°E	6.9	2.6	−0.1	A	1,640	2003/12/10, Mw 6.8
TTN004; 11234401.CVA; 22.910°N, 121.129°E	3.0	−0.7[b]	−0.6[b]	LONT; 22.908°N, 121.122°E	5.1	−1.0	−0.4	A	760	2003/12/10, Mw 6.8
TCU052; T030001.263; 24.198°N, 120.739°E	350.5	687.9	−357.7	M324; 24.222°N, 120.735°E	397.2	845.1	−342.3	B	2,700	1999/09/20, Mw 7.6 Hanging wall
TCU074; T202001.263; 23.962°N, 120.962°E	−66.4	137.1	−193.8	HTZS; 23.976°N, 120.974°E	−60.3	128.4	−187.7	B	1,950	1999/09/20, Mw 7.6 Hanging wall
TCU078; T020001.263; 23.812°N, 120.846°E	−21.9	72.9	−121.2	M408; 23.779°N, 120.841°E	−16.3	83.2	−137.2	B	3,810	1999/09/20, Mw 7.6 Hanging wall
TCU079; T121001.263; 23.839°N, 120.894°E	−27.8	101.6	−71.9	M509; 23.816°N, 120.890°E	−31.0	75.5	−151.9	B	2,730	1999/09/20, Mw 7.6 Hanging wall
TCU137; 26726300.IDS; 24.185°N, 120.922°E	207.4	216.3	−247.8	G099; 24.173°N, 120.887°E	155.8	301.3	−259.9	B	3,810	1999/09/20, Mw 7.6 Hanging wall
TCU102; T062001.263; 24.249°N, 120.721°E	−17.7	−68.0	87.5	G103; 24.262°N, 120.710°E	−10.0	−59.2	66.3	B	1,730	1999/09/20, Mw 7.6 Foot wall
TCU060; T240001.263; 24.225°N, 120.644°E	−2.5[b]	−53.3[b]	62.2	AF26; 24.223°N, 120.643°E	−6.7	−38.3	55.8	B	232	1999/09/20, Mw 7.6 Foot wall
TCU054; T111001.263; 24.161°N, 120.675°E	−2.8[b]	−61.5	57.5[c]	M805; 24.173°N, 120.672°E	−11.5	−47.4	79.8	B	1,230	1999/09/20, Mw 7.6 Foot wall
TCU056; T024003.263; 24.159°N, 120.624°E	−0.2[b]	−61.6[b]	46.2	AF17; 24.158°N, 120.624°E	−7.4	−32.1	59.1	B	96	1999/09/20, Mw 7.6 Foot wall
TCU120; T161001.263; 23.980°N, 120.613°E	−1.9[b]	−25.8[b]	70.8	M365; 23.968°N, 120.619°E	−15.9	−21.0	70.0	B	860	1999/09/20, Mw 7.6 Foot wall
TCU076; T091001.263; 23.908°N, 120.676°E	−6.5[b]	−28.0	87.3	AF11; 23.896°N, 120.676°E	−17.7	−32.1	88.2	B	1,350	1999/09/20, Mw 7.6 Foot wall

Data source: 2003 Mw6.8 Chengkung earthquake (A) by Chen et al. (2006); 1999 Chi-Chi earthquake (B) by Yu et al. (2001)

[a] Record of PGA less than 60 cm/s^2

[b] Permanent displacement less than three standard deviation values

[c] No correction

Fig. 6 Top: Observed acceleration for the east–west component at station TCU052 from the 1999 Chi-Chi, Mw 7.6 earthquake. Middle: Velocities integrated from uncorrected (red) and corrected (black) accelerations. Bottom: Displacements for the uncorrected (red) and corrected (black) cases. After baseline corrections and double integration, 357.7 cm of permanent westward displacement was obtained. The nearest GPS station, at a distance of about 2.7 km, observed a westward displacement of 342.3 cm. Vertical lines marked by T1, T2, and T3 indicate the correction time points. The thick red line plotted in the velocity record shows the correction baseline

TCU052 Raw data, Filename=T030001.263, E-W Component

TCU052 Corrected and Raw Data, Filename=T030001.263, E-W Component

TCU052 Corrected and Raw Data, Filename=T030001.263, E-W Component

station and GPS station is less than 4 km for the Chi-Chi earthquake in the hanging wall region and less than 2 km elsewhere.

   Figure 2 displays the raw and corrected data of the east–west component of station TTN014 from the 2003/12/10 Mw=6.8 Chengkung earthquake. After applying our baseline correction method and integrating twice, a permanent eastward displacement of 9.4 cm was recovered. An almost co-site GPS station

observed a 9.3-cm eastward displacement. Vertical lines marked by T1, T2, and T3 in Fig. 2 indicate the correction time points. The thick red line plotted in the velocity history shows the correction baseline. The GPS and strong-motion stations are both operated by the CWB in continuous mode. The GPS measurement did not show any postseismic deformation.

   In our method, the time point for selecting T1 is clear. However, a problem exists for selecting T3 due
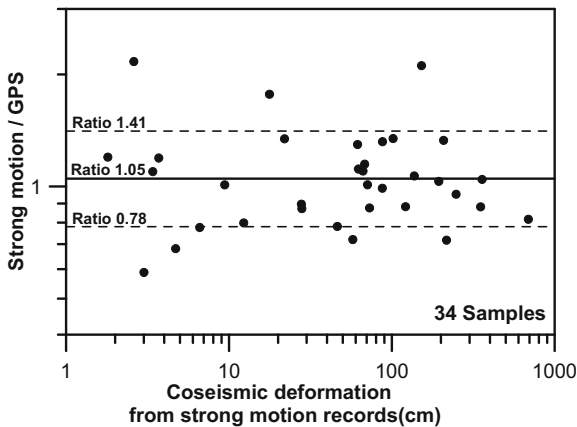
Fig. 7 Ratio of the permanent displacements determined from strong-motion data and from GPS plotted against the displacement determined from the strong-motion data. Solid line shows the mean value and dashed lines show the one standard deviation limits

to the fact that "overshooting" can occur in the corrected displacement history. We suggest that T3 should be chosen at the point where the overshooting has ended and the ground has returned to the permanent displacement position. Figure 6 shows a typical case for selecting T3. The strong-motion record is the east–west component at station TCU052 from the 1999 Chi-Chi, Mw=7.6 earthquake. After baseline correction and double integration, a permanent westward displacement of 357.7 cm was obtained. It is in good agreement to the measurement of a displacement of 342.3 cm at the nearest GPS station about 2.7 km away.

Table 1 lists the permanent displacement results for 16 strong-motion records analyzed in this study and the nearest GPS measurements from Yu et al. (2001) and Chen et al. (2006). A total of 34 components of coseismic displacements were obtained. We did not analyze the records for peak ground acceleration (PGA) less than 60 cm/s^2 because of poor signal-to-noise ratios. We also neglected values of permanent displacements that are less than three standard deviation values.

Figure 7 shows 34 samples of the ratios of coseismic displacements determined from strong-motion data and from GPS observations. The average ratio is about 1.05 with most samples located in the range from 0.78 to 1.41 for one standard deviation limits. Therefore, our results indicate that coseismic displacements from a few centimeters to meters can be determined from the strong-motion records.

Generally, the difference between coseismic displacements determined from strong-motion data and from GPS observations is larger than the error in the results of shake-table tests. We suggest that this is mostly due to source effects. Coseismic displacements determined from strong-motion data contain earthquake source effects. Larger earthquakes have stronger low-frequency signals and more complex source-time functions. However, shake-table "step" tests have well-known sources and more high-frequency signals. The displacements are easier to be recovered and the recovery precision is higher than using earthquake records.

In this study, we have compared the coseismic displacements determined from strong-motion data with those from GPS observations. It provides a first-order estimation of the upper and lower bounds using our method because most of the GPS and strong-motion stations listed in Table 1 are not located at the same site.

5 Further examination

We also applied our method to all of the horizontal strong-motion records from the Chi-Chi earthquake
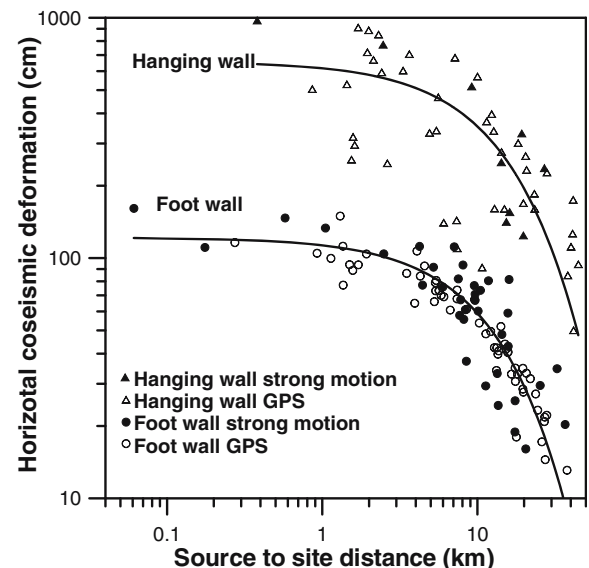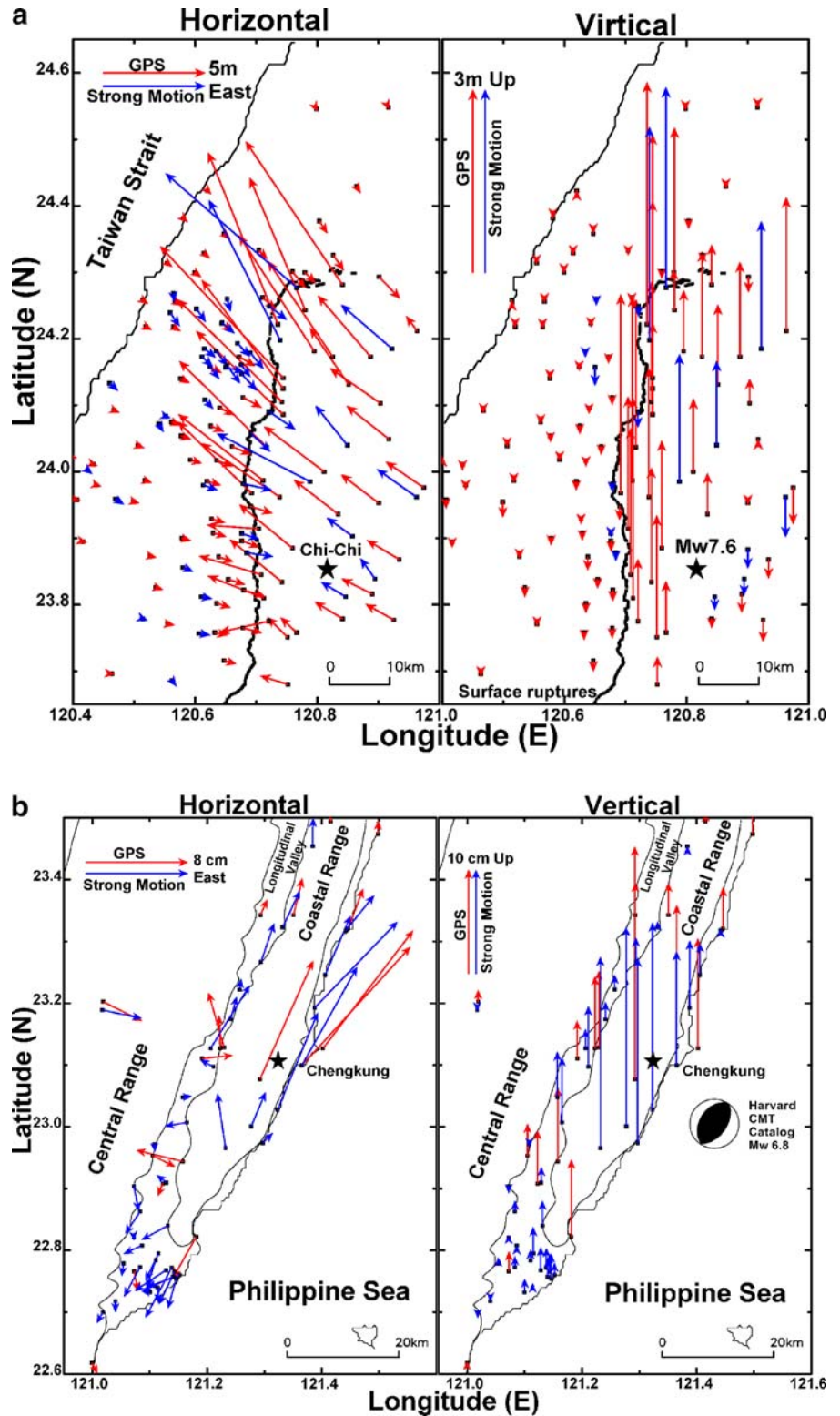

Fig. 8 (**a**) Horizontal coseismic deformation from GPS and strong motion data versus distance for Chi-Chi earthquake. Triangles and circles show measurements from hanging wall and foot wall, respectively. The two curves show the least-squares fit results

Fig. 9 (a) Map showing the coseismic ground slips (blue vectors) determined by strong-motion records and GPS slips (red arrows) from Yu et al. (2001) for both the horizontal and the vertical components of the 1999, Chi-Chi earthquake. (b) Map showing the coseismic ground slips (blue vectors) determined by strong-motion records and GPS slips (red arrows) from Chen et al. (2006) for both the horizontal and the vertical components of the Chengkung earthquake

recorded in the near source region. For comparison, we plot horizontal coseismic deformations from GPS and strong-motion data versus the distances (R) from the rupture surface to the sites. Results are shown in Fig. 8, and the two results agree favorably with each other. The Chi-Chi earthquake is a typical thrust event (Chang et al. 2000). The horizontal coseismic deformation characteristics are quite different between hanging and footwalls. Using the attenuation formula of Wu et al. (2001) and data from GPS (Yu et al. 2001) and strong-motion records, we obtained two least-squares fit curves for the coseismic deformation (D) of the Chi-Chi earthquake:

for hanging wall

$$\log(D) = 2.279 + 0.300\,M_w - 0.0198\,R - \log(R + 0.00871 \times 10^{0.5Mw}) \qquad (4)$$

for foot wall $\qquad\qquad\qquad\qquad\qquad (5)$

$$\log(D) = 1.912 + 0.252\,M_w - 0.0239\,R - \log(R + 0.00871 \times 10^{0.5Mw}).$$

Figure 8 also shows these two least-squares fit curves. Although it may not provide a good constraint for studying the attenuation relationship since records from only one event are used, the curves give a good reference for the examination of coseismic deformation using strong-motion data.

We further applied our method to all of the strong-motion records from the Chi-Chi and Chengkung earthquakes recorded in the near source region. Figure 9a and b shows the ground slips from strong-motion records, which are very consistent with the GPS slips (Chen et al. 2006; Yu et al. 2001) for both Chi-Chi and Chengkung earthquakes, respectively. This further validates our method. The Chengkung earthquake produced a large amount of afterslips (Lee et al. 2006). Thus, in Fig. 9b, only continuous GPS measurements were used.

6 Conclusions

We have proposed a new approach to baseline corrections to recover the coseismic displacements from strong-motion records. The sources of the baseline shifts are numerous, as pointed out by Boore et al. (2002) and Boore and Bommer (2005). Tilting of the ground is one of the causes, for example, and at least two baseline correction steps are necessary. For the cases shown in Figs. 2 and 6, we have tried to apply a single baseline correction to determine the displacement. However, the results did not agree with the GPS observations. Certainly, two-step baseline corrections are just an empirical approach before the sources of the baseline shifts are clearly understood and six-component strong-motion records are available (Graizer 1989, 2005; Niggbor 1994; Trifunac and Todorovska 2001).

In this study, we developed the baseline correction method based on the work of Iwan et al. (1985) and Boore (2001). We examined our method using an extensive set of data from shake-table tests of a known displacement on 249 accelerographs. Our baseline correction method recovered about 97% of the actual displacement from the shake-table data. We then applied this baseline correction method to compute coseismic displacements from the strong-motion data of the Chi-Chi and Chengkung earthquakes. Our results agree favorably with the coseismic displacements determined by the GPS measurements at nearby sites. The ratio of seismic to geodetic displacement varies from 0.78 to 1.41, with an average ratio of about 1.05. Our baseline correction approach is validated by comparisons for both shake-table tests and for actual earthquakes.

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