Study on the coseismic displacement field of the 1999 Chi-Chi earthquake based on strong motion data

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Abstract: The Whitney (2018) linear baseline correction method is used to analyze the near-fault strong motion data of the 1999 Chi-Chi earthquake and quickly calculate the co-seismic displacement. The feasibility of this method is verified by comparison with the coseismic displacement data of adjacent GPS stations. The results show that the coseismic displacement of the hanging wall is significantly larger than that of the foot wall, and largest displacements reached 707.0cm north and 369.7 cm up respectively, and occurred at the hanging wall station TCU052. The results in this paper can provide references for the rapid identification of coseismic displacements using strong motion data.

1. Introduction
Coseismic displacement is the ground deformation caused by fault dislocation during an earthquake, which can have a great impact on earthquake magnitude and slip distribution compared to seismic waveform records \cite{1}. This is of great importance to post-earthquake ground deformation, earthquake rupture model and process inversion, seismic design of large-span engineering structures, early earthquake warning, and rapid post-earthquake damage assessment. Currently, coseismic displacements are mainly obtained through geodetic techniques such as global positioning system (GPS) and direct calculation of near-field strong motion records. In the 1992 Landers earthquake in the United States, GPS was first used to obtain coseismic displacement data \cite{2}. The use of GPS as an accurate geodetic means makes it possible to obtain coseismic displacements with millimeter-level accuracy and stable results, but it also has some disadvantages such as high calculation complexity, longer output period (usually several days to several weeks), large difficulty in data sharing, the results being greatly affected by aftershocks. However, coseismic displacements obtained from strong motion observation records are slightly lower in terms of accuracy, usually at the centimeter level, but this method has the advantages of low calculation complexity, short output period, ease of data sharing, and single record not being affected by aftershocks \cite{3}. Also, considering that today GPS stations are still sparse compared to strong motion stations in terms of distribution, the use of strong motion observation records to extract the coseismic displacement field is a fast and economical option. When coseismic displacements are calculated by using acceleration records, ideally, a stable and non-drifting permanent ground displacement can be obtained after the acceleration records are integrated twice, and the coseismic displacement can be identified from the displacement time history. But in practical applications, due to ground tilt \cite{4, 5}, instrument defects \cite{6}, background noise \cite{7}, and other reasons, the velocity and acceleration are not stable, and the calculated coseismic displacement is affected, so the baseline correction method proposed by Whitney is used to calculate the coseismic displacement.
displacement time history obtained by acceleration integration would show baseline shifts, which still remains an unchanged problem. It means that the acceleration and ground velocity are not zero and the displacement is not a constant after the earthquake. This unreliable result makes it necessary to perform baseline corrections. In other words, baseline corrections are the key to obtaining coseismic displacements.

Before 1970, baseline corrections were mainly done by fitting the baseline of acceleration time history with a parabola [8]. Trifunac (1971) proposed to use the method of least squares to fit acceleration and velocity time history [9]. Iwan et al. (1985) divided the baseline shift of acceleration time history into $\alpha_{\text{sm}}$ of the strong motion phase ($t_1 \leq t \leq t_2$) and $\alpha_{\text{ar}}$ after the strong motion phase ($t_2 \leq t \leq t_r$) [6]. In this case, how to determine the segmentation parameters $t_1$ and $t_2$ is the key to the method. Iwan determined the two parameters to be the moment when the acceleration time history equals 50 cm/s$^2$ for the first and last time respectively. This determination method is based on the hysteresis effect of specific digital strong motion seismographs and may not be applicable for other types of data [10]. Boore (1999, 2001), on the other hand, set $t_1$ and $t_2$ as free parameters ($t_1 \leq t_2 \leq t_r$) [10, 11]. He found that different values of $t_1$ and $t_2$ had a significant impact on the final correction results. Therefore, he suggested that the moment $t_1$ should satisfy the requirement that the fitted value of velocity was zero after baseline initialization (minus the average value of records before the earthquake). Although Boore’s correction results fitted well with the displacements observed by GPS, the choice of $t_1$ and $t_2$ was too subjective. Wu&Wu (2007) proposed a flatness index $f$ to determine the segmentation parameter $t_2$, so as to reduce the subjectivity of segmentation parameter selection through iterative computations [12]. Zhou et al. (2013) used this method to analyze some records of the Great East Japan Earthquake and found that the correction results were not satisfactory [13], indicating the lack of generality of the method. Wang et al. (2011) proposed an improved automatic empirical algorithm to determine $t_1$ and $t_2$ [1]. By limiting both parameters within a certain range, they applied the grid search algorithm and used a step function to fit the corrected displacements, and the best-fit $t_1$ and $t_2$ were the optimal solution. The use of this method not only enables automatic calculations but also reduces the subjectivity of the selection of $t_1$ and $t_2$, which is a great improvement. However, it should also be noted that the method requires setting many correction parameters and is based on empirical criteria summarized from single-event characteristics [14], indicating that the method is of relatively high complexity and its generality still needs to be further validated. Whitney (2018) proposed a linear correction method [15], in which he integrated the two segmentation parameters into one and determined it based on a completely objective determination criterion. In addition, he validated the applicability of this method based on the few records of the 2015 Nepal earthquake with a magnitude of Mw7.6, the 2008 Ölfus earthquake in Iceland with a magnitude of Mw6.3, and the 1999 Chi-Chi earthquake with a magnitude of Mw7.6. In this method, single-segment correction is used, which means the additional setting of correction parameters is not required. Except for the need to determine the linear drift trend of velocity and displacement, automatic calculations can be achieved, which largely reduces the subjectivity incurred by using the previous manual correction method. In order to further verify the generality of this method to obtain coseismic displacements, this paper tends to select an earthquake case with a large amount of strong motion data and GPS coseismic displacement data for comparison and verification, so as to provide an effective method to obtain coseismic displacements quickly for similar earthquakes in the future.
2. Data and Method
At 1:47 a.m. local time on September 21, 1999, in Taiwan, a major earthquake with a magnitude of Mw7.6 occurred in Chi-Chi Township, Nantou County, central Taiwan. The epicenter was at 23.85°N, 120.82°E, and the source depth was about 8 km. The earthquake was caused by the dislocation of the Chelungpu fault, resulting in a surface rupture of up to 100 km \[^{[16]}\], which was a typical reverse-fault earthquake. There is a dense network of strong motion observation stations and GPS observation stations in Taiwan, and thus a large number of strong motion observation records and surface deformation data have been obtained \[^{[17, 18]}\], which provides strong support for verifying the coseismic displacement obtained from strong motion data using GPS data. Under the conditions that GPS stations were less than 5 km away from the strong motion stations and the stations were less than 100 km away from the epicenter, a total of 60 pairs of data were selected for validation of the Whitney linear correction method. Among them, the closest two types of stations were AF17 and TCU056, which were 111 m apart. M509 and TCU079 were the closest to the epicenter, both of which were 8 km away from the epicenter. The station M901 and TCU098 were the farthest to the epicenter, both of which were 98.4 km away from the epicenter. The distribution of strong motion stations and GPS stations is shown in Figure 1. Whitney's linear baseline correction method (2018) was used.

3. Calculation of Coseismic Displacement Field
Figure 2a showed the uncorrected acceleration (Acc.), velocity (Vel.), and displacement (Disp.) time history of the station TCU079. It could be seen that the baseline drift almost could not be observed in the original acceleration time history, but the east-west and north-south components of the velocity time history obtained by integration showed obvious linear drift, and the vertical component of the displacement time history showed a linear drift trend. Firstly, the baseline correction was performed for the three-component record of this station using the Whitney (2018) linear correction method, and the
Figure 2. Uncorrected (a) and corrected (b) acceleration (up), velocity (middle), displacement (down) of station TCU079.
corrected time history was shown in Figure 2b. The displacement time history in the figure also showed the coseismic displacement of the GPS station M509. From the figure, it could be known that due to the earthquake, the station TCU079 moved 154.7 cm to the west, 66.5 cm to the north, and 20.0 cm to the down, and the GPS station moved 151.9 cm to the west, 75.5 cm to the north, and 31 cm to the down, which were highly consistent.

Figure 3 showed the comparison of the selected strong motion station and the corresponding GPS station in terms of coseismic displacement. As we could see, the displacement field distribution, displacement direction and amplitude obtained from the two types of data showed good overall consistency. The horizontal displacement field on both sides of the fault showed inward convergence and the vertical displacement field on both sides of the fault showed upward and downward movement in opposite directions, with the west side mainly downward and the east side mainly upward. The displacement field distribution on both sides revealed that reverse thrust faulting took the largest part, with the west side of the fault as the foot wall and the east side as the hanging wall. Both maximum horizontal and vertical displacements of the GPS data were at the station M324, which was located at the hanging wall and 40.87 km away from the epicenter. The station moved 324.3 cm to the west and 845 cm to the north. Its horizontal displacement reached 905.09 cm, and its vertical displacement reached 397.2 cm upward. The strong motion station closest to M324 was TCU052 with a distance of 2.5 km, and the station moved 707.0 cm to the north and 369.7 cm to the top. In addition, the station G104 had a relatively large displacement of GPS data, which was 273.1 cm in the east-west direction, 652.2 cm in the north-south direction, and 299.8 cm in the vertical direction. The strong motion station closest to the station G104 was TCU068 with a distance of 4.04 km, and it moved westward 625.7 cm and upward 352.6 cm, and the coseismic displacements of the two data sets were well fitted. The unusual records appeared in the east-west component of the station TCU052 and the north-south component of the station TCU068. Since these two records had a bilinear drift trend in the velocity time history, the linear correction method in this paper was not applicable. Therefore, the velocity pulse identification method proposed by Whitney [15] was used to extract the coseismic displacements for these two records. Also, it was found that they matched well with the GPS coseismic displacements (see Figure 3a).
4. Conclusions
Due to background noise and ground tilt in strong motion data, the problem of baseline drifts usually occurs when strong motion observation records are used to identify coseismic displacements. The existing baseline correction methods mainly focus on improving the two-segment correction method proposed by Iwan. Although these methods have achieved some practical results, there are still two important problems that have not been solved. One is that the subjectivity and empirical nature of parameter selection still exist, and the other is that many methods have limited applications, and there is not a general and feasible method for identifying coseismic displacements for different earthquakes that occurred, that is, these methods are lack of generality. Whitney’s linear baseline correction method reduces two-segment correction to single-segment correction. By means of this method, not only is the number of segmentation parameters reduced but also the determination of the segmentation parameters is totally based on objective constraints, which avoids the subjectivity of parameter selection. Besides, the method is easy to operate. Except for the need to observe whether the velocity and displacement time history have a linear trend, automatic calculations can be realized in this method.

In this paper, Whitney’s linear correction method was used to identify the coseismic displacements of the 1999 Chi-Chi earthquake. The results showed that the coseismic displacement of the hanging wall of the fault was significantly larger than that of the footwall, and the displacement of the station TCU052 at the hanging wall of the fault was the largest, with 707.0 cm and 369.7 cm northward and upward, respectively. Comparing figures through calculation with GPS data, it was found that the method could reach a considerable stability. The only drawback was that the method required a linear baseline drift trend of the velocity or displacement time history, which somewhat limited the applicability of the method. It should also be noted that the method has mainly been validated for its applicability to obtaining the coseismic displacements of earthquakes with a magnitude of Mw6.0 and above. Therefore, further research shall be conducted to verify its applicability to different types and magnitudes of earthquakes based on a large number of other types of seismic data in combination with GPS data.

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Reference
[1] WANG R, SCHURR B, MILKEREIT C, et al. (2011) An improved automatic scheme for empirical baseline correction of digital strong motion records. Bulletin of the Seismological Society of America, 101(5): 2029-2044.
[2] SHEN Z-K, JACKSON D D, FENG Y, et al. (1994) Postseismic deformation following the Landers earthquake, California, 28 June 1992. Bulletin of the Seismological Society of America, 84(3): 780-791.
[3] Jin M-P, Li Zh-L, Wang R-J. (2017) Coseismic displacement field and slip model derived from near-source strong motion records of W7.0 Kumamoto,Japan,earthquake. Acta Seismologica Sinica, 39(06): 819-830.
[4] GRAIZER V M. (2005) Effect of tilt on strong motion data processing. Soil Dynamics and Earthquake Engineering, 25(3): 197-204.
[5] GRAIZER V. (2006) Tilts in Strong Ground Motion. Bulletin of the Seismological Society of America, 96(6): 2090-2102.
[6] IWAN W D, MOSER M A, PENG C-Y. (1985) Some observations on strong motion earthquake measurement using a digital accelerograph. Bulletin of the Seismological Society of America, 1985, 75(5): 1225-1246.
[7] CHIU H-C. (1997) Stable baseline correction of digital strongmotion data. Bulletin of the Seismological Society of America, 87(4): 932-944.
[8] HUDSON D E, NIGAM N, TRIFUNAC M D. (1969) Analysis of Strong motion Accelerograph Records [M]. Chilean Association on Seismology and Earthquake Engineering. Santiago, Chile.

[9] TRIFUNAC M D. (1971) Zero baseline correction of strong motion accelerograms. Bulletin of the Seismological Society of America, 61(5): 1201-1211.

[10] M. BOORE D. (2001) Effect of Baseline Corrections on Displacements and Response Spectra for Several Recordings of the 1999 Chi-Chi, Taiwan, Earthquake. Bulletin of the Seismological Society of America, (91): 1199-1211.

[11] D. M. BOORE. (1999) Effect of baseline corrections on response spectra for two recordings of the 1999 Chi-Chi, Taiwan, earthquake [M]. US Department of the Interior, US Geological Survey.

[12] WU Y-M, WU C-F. (2007) Approximate recovery of coseismic deformation from Taiwan strong motion records. Journal of Seismology, 11(2): 159-170.

[13] Zhou B-F, Yu H-Y, Wen R-ZH, et al. (2013) A new way of permanent displacement identification. China Civil Engineering Journal, (2): 135-140.

[14] Jin M-P, Wang R-J. (2013) Rapid slip inversion using co-seismic displacement data derived from near-source strong motion records. Chinese Journal of Geophysics, 56(4): 1207-1214.

[15] WHITNEY R. (2018) Estimating coseismic ground displacement during the 2015 Gorkha, Nepal, earthquake from accelerometric data at KATNP station. Soil Dynamics and Earthquake Engineering, (107): 363-373.

[16] CHEN W, HUANG B-S, CHEN Y, et al. (2004) 1999 Chi-Chi Earthquake: A Case Study on the Role of Thrust-Ramp Structures for Generating Earthquakes. Bulletin of the Seismological Society of America, (91): 986-994.

[17] YANG M, RAU R-J, YU J-Y, et al. (2000) Geodetically observed surface displacements of the 1999 Chi-Chi, Taiwan, Earthquake. Earth, Planets and Space, 52(6): 403-413.

[18] YU S-B, KUO L-C, HSU Y-J, et al. (2001) Preseismic deformation and coseismic displacements associated with the 1999 Chi-Chi, Taiwan, earthquake. Bulletin of the Seismological Society of America, 91(5): 995-1012.