17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Baseline Correction Method for the Multiple Fling Steps Recordings of the 2008 Wenchuan, China, Earthquake

X.X. Yao[(1)], T. Kishida[(2)], Y.F. Ren[(3)], R.Z. Wen[(4)]

[(1)] *PhD Student, Institute of Engineering Mechanics, China Earthquake Administration, yaoxinxiniem@126.com*
[(2)] *Assistant Professor, Khalifa University of Science and Technology, tadahiro.kishida@ku.ac.ae*
[(3)] *Professor, Institute of Engineering Mechanics, China Earthquake Administration, renyefei@iem.net.cn*
[(4)] *Professor, Institute of Engineering Mechanics, China Earthquake Administration, ruizhi@iem.ac.cn*

Abstract

With the increasing number of ground-motion data, many strong motion accelerogram show fling effects near fault rupture. However, these data often show the nonzero velocity and the drift displacement at the end of shaking by integrating the recorded acceleration time series. These drifts could be resulted from errors such as tilting of strong motion seismograph due to great surface deformation, low resolution ratio of instrument and fatigue of sensor existed in the apparatus and other possible causes. Therefore, baseline correction, as one of steps in data processing, is essential to remove these errors by keeping residual displacements.

These permanent residual displacements are key to understand the damages at the recording sites, but also provide a reference for earthquake focal mechanism study. Moreover, the low frequency (long-period) signals, including the residual displacements, are very important for earthquake engineering design, such as long-span bridges, tunnels, high-rise buildings, and dams. However, these fling effects are typically often removed by applying high-pass filters through typical strong motions standard data processing method of strong ground motions [1]. For example, in 1999 M7.0 Chi-Chi earthquake, several stations recorded the fling effects, but these residual displacements are not much used for engineering design practice. Therefore, this study investigates the methodology of baseline correction method to preserve the fling effects, whereas a typical approach removes these by applying high-pass filters and baseline corrections.

During 2008 Ms8.0 Wenchuan Earthquake, there are 450 stations recorded main earthquake, including 93 stations located near the Longmen-Mountain fracture zone. Some Chinese researcher used the baseline correction method proposed by [2,3] to preserve the fling effects of near fault recordings. However, the recorded time series show that there are two or more line-drifts in the velocity time series after integration of the acceleration time series. This observation means there are at least two fling steps in the recorded time series during 2008 Ms8.0 Wenchuan Earthquake. If the records are processed by the traditional methods [2,3], the fling steps would be altered obviously.

This study uses acceleration time series during 2008 Ms8.0 Wenchuan Earthquake recorded at 51WCW station to investigate data processing method to preserve fling effects. The three-component time series clearly show two large fling steps, which are illustrated through data processing. These data are unique and have not been discussed how to extract these displacements. The study also shows a limitation of the data processing method presented in the past studies when the multiple fling steps exist in the recorded time series. Finally, a new data processing method is presented to extract the multiple fling steps from the data by performing baseline corrections.

Keywords: Fling effect; Permanent displacement; Wenchuan earthquake; Baseline correction;

1. Introduction

Fault ruptures produce permanent displacements at ground surface causing significant damages on the adjacent surface and underground structures [4,5]. Recorded near-fault strong ground motions often includes the permanent displacement, which is called fling step in engineering term, and causes a long-period pulse that is distinct from directivity pulse. These ground motions are utilized for seismic design of several structures such as long-span bridges, base-isolated structure [6], pipelines and tunnels [7], and structural foundations [8]. However, the recorded ground motions which contains fling effects are limited [9] because the static displacement is typically removed via ground motion processing to remove low frequency noises from seismological signals. Due to the advent of digital instruments, a number of strong-motion has increased significantly which were recorded near fault ruptures. Therefore, it is useful to develop consistent and reliable data processing method to sustain fling effects by removing baseline errors.

Many studies presented data processing methods to sustain permanent displacements. Some studies suggested the method which assumes that the baseline drift occurs due to the tiling of the instrument [10,11,12]. Other studies proposed the method by fitting piece-wise linear models to velocity time series [2,3,13,14,15,16,17]. Since there is no physical evidence of source of baseline drift, these approaches are techniques to approximately extract the permanent displacements from strong motions [3]. Therefore, several studies performed the comparison of extracted permanent displacement with geodetic measurements to understand the uncertainties in the resulted values [9,15,16]. Because of these issues, the available strong motions which contains the fling effects are limited.

During 2008 Ms8.0 Wenchuan Earthquake, several stations near fault rupture recorded the strong motions which include the fling effects. However, there was a difficulty to remove baseline errors by fitting piece-wise linear method to sustain the permanent displacement for these records because 2008 Ms8.0 Wenchuan Earthquake have two strong ruptures where the past approaches assume that a single fling step exists in the ground motions. This study describes the limitation in the previously suggested methodology to remove baseline errors when the multiple fling step exists in the ground motions, then propose the algorithm which can process the ground motions with multiple fling steps by expanding the existing piece-wise linear fitting approaches. We also illustrate the importance of the proposed algorithm comparing with the results by the previous studies.

2. 2008 Ms8.0 Wenchuan Earthquake

Ms8.0 Wenchuan Earthquake occurred on May 12, 2008. Two major faults ruptured, where one is Beichuan fault which extends 310 km with strike direction toward to southeast. The other is Pengguan fault locating parallel to the southeast segment of Beichuan fault with the rupture length of 130 km. The rupture on Beichuan fault has two subevents; hence the inversion results showed three fault ruptures [18,19,20,21]. The southeast segment of Beichuan fault and Pengguan fault ruptures about the same time with the rupture length of 130 km. The fault style is oblique right-lateral thrust slip. The northeast segment of Beichuan fault slipped largely right-lateral direction with the rupture length of 180 km [18,19]. The northeast segment started to rupture 44 s after the southwest segments ruptured, and these ruptures overlap by 4 s based on the inversion results by [19]. Therefore, two strong shakings are recorded near the boundary between southeast segment of Beichuan fault/Pengguan fault and northwest segment of Beichuan fault. This study investigates data processing method using the strong motion recorded at 51WCW station which is located near the south edge of Beichuan fault with the closest distance to fault rupture of approximately 18 km.

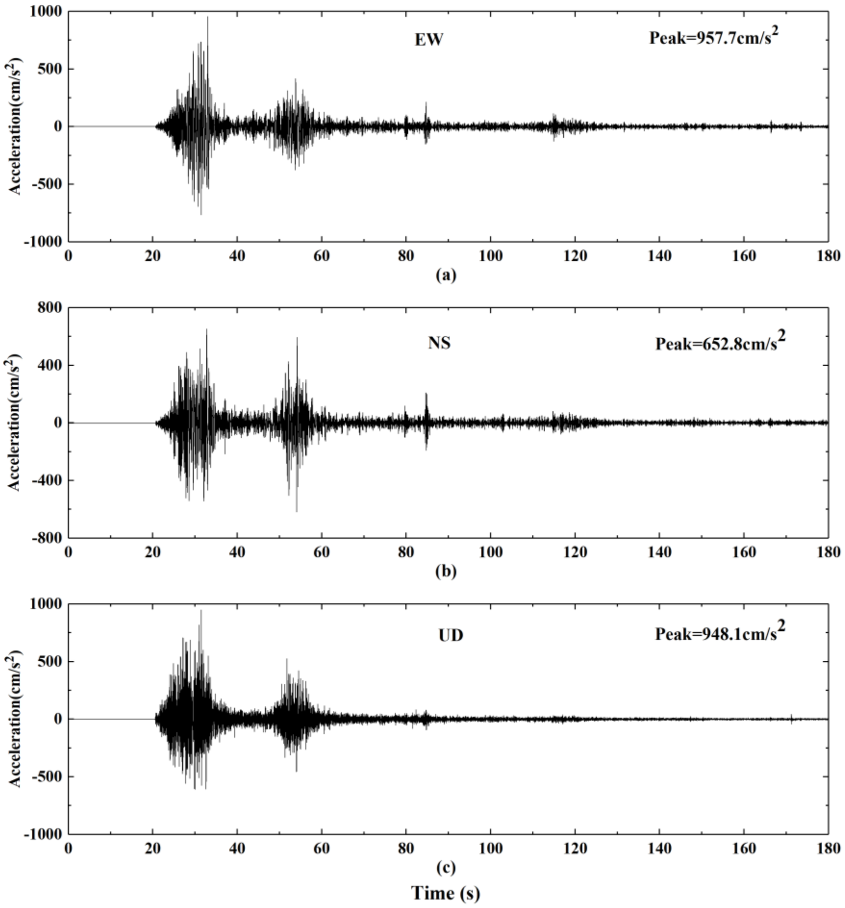

Fig. 1 – Unprocessed acceleration time series of 51WCW station (a) EW, (b) NS, (c) UD component.

Fig.1a-1c show the recorded acceleration time series for NS, EW, and UD directions. There are two major ruptures from recordings where the first rupture is from southwest and the second one from northeast segments.

3. Data Processing Method in the Previous Studies

[2,3] presented the algorithm to perform baseline correction on the recorded strong motions. The velocity time series are divided into three segments, where a piece-wise linear model is fitted to remove baseline error. These segments are defined by $t = t_0$, t_1, t_2 and t_3 where the start and end times of i^{th} segment are t_{i-1} and t_i, respectively. The t_0 and t_3 are start and end time of time series, where t_1 to t_2 are free parameters. The mathematical formula assumes that static displacement occurs at 2^{nd} segment from t_1 to t_2; hence a single fling step exists within strong shakes. The displacement drift in the first segment is generally removed by subtracting the pre-event mean from the acceleration time series [3]. The acceleration time series are integrated into velocity time series, then that in the last segment are fitted by linear trend as follows.

$$V_3(t) = b_3 + a_3 t \qquad (1)$$

Subscript in Eq. (1) presents the segment number, and a_3 is baseline error that can be removed from acceleration time series from t_2 to t_3. Between time interval from t_1 to t_2, the baseline error is determined to satisfy that the drift velocities at t_1 and t_2 equal to the values at the end of 1^{st} and the beginning of 3^{rd} segments of a piece-wise linear model, respectively. Therefore, the slope of velocity time series at the 2^{nd} segment is obtained as follows:

$$a_2 = [V_3(t_2) - V_1(t_1)]/ (t_2 - t_1) \tag{2}$$

Since pre-event mean is already removed, $V_1(t_1) = 0$ in Eq. (2). By subtracting a_2 and a_3 from acceleration time series from t_1 to t_2, and t_2 to t_3, respectively, the baseline-corrected acceleration time series are obtained. Finally, the coordinating velocity and displacement waveforms will be derived from the corrected acceleration. Choosing t_1 and t_2 is the key in data processing that influences on the resulted static displacement depending on the records [3].

4. Proposed Data Processing Method

Piece-wise linear approach can be expanded by assuming that multiple fling steps exist within strong shakes. This situation is similar to the one observed in Fig.1 during 2008 Ms8.0 Wenchuan Earthquake. When n fling steps exist in the ground motion, $(2n + 1)$ segments are modeled to correct the baseline error by piece-wise linear model. The i^{th} segment is defined from t_{i-1} to t_i. The fling steps exist at the segment where $i = 2k$ ($k = 1, \ldots, n$), and the static displacement does not occur at $i = 2k - 1$ ($i = 1, \ldots, n+1$). At the segment when $i = 2k - 1$, velocity time series are linearly fitted by following formula:

$$V_i(t) = b_i + a_i\, t \tag{3}$$

When $i = 2k$, the baseline error is determined to satisfy that the drift velocities at t_{i-1} and t_i equal to the values at the end of $(i\text{-}1)^{th}$ and the beginning of $(i+1)^{th}$ segments of a piece-wise linear model, respectively. Therefore, the slope of velocity time series at the i^{th} segment ($i = 2k$) is obtained as follows:

$$a_i = [V_{i+1}(t_i) - V_{i-1}(t_{i-1})]/ (t_i - t_{i-1}) \tag{4}$$

The resulted a_i are removed from acceleration time series of corresponding segments. By using Eqs. (3) and (4), the algorithm by [2,3] are expanded to remove baseline error from multiple fling-step motions. Based on the authors' literature review, Eqs. (3) and (4) have not been presented by any study to process these motions in Fig.1.

5. Evaluation of Fling Step Timings

Fig.2 shows the velocity time series in EW direction, in which the baseline error increase linearly at the end of records indicating that a constant baseline error exists in acceleration time series.

Fig.3 shows standard deviation of velocity time series detrended by the linear regression model from (a) $t = 0$ to 20 s, and (b) $t = 160 - 180$ s in Fig.2. This approach was presented by [14] to examine when the baseline shift occurs. From the figure, the two major shifts occur especially in Fig.3(b) from $t = 21 - 32$ s, and $t = 50 - 58$ s. These timings approximately correspond to two major ruptures in Fig. 1. Therefore, it is confirmed that multiple fling steps occurred in the strong motions.

Fig.4 shows the standard deviation of velocity slopes subtracted by the constant value from the linear trend from (a) $t = 0$ to 20 s, and (b) $t = 160 - 180$ s in Fig.2. This approach is proposed in this study because it shows clear offsets of standard deviation for all three components. Similarly, two major shifts of standard deviations exist corresponding to the two major ruptures in Fig. 1. Given the geodetic and geophysical observations from the past studies [18,19,20] with clear baseline shifts in Fig.3 and 4, it is reasonable to conclude that the strong motions recorded at station 51WCW includes two fling steps.

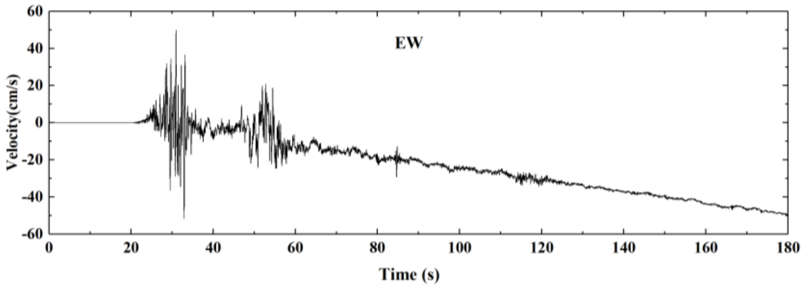

Fig.2 – The Velocity time series of 51WCW station in EW component

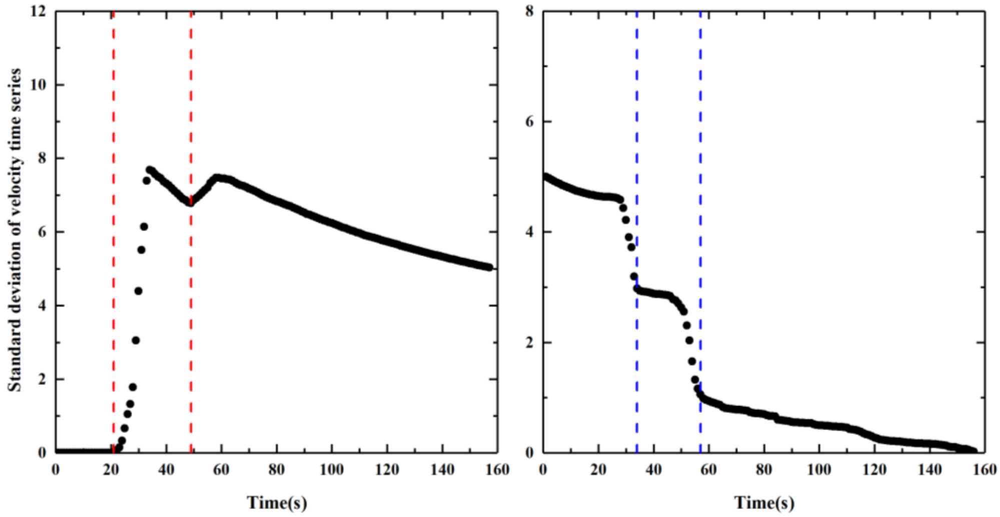

Fig.3 – Variation of standard deviation of velocity time series detrended by the linear regression model from (a) t = 0 to 20 s, (b) t = 160 – 180 s.

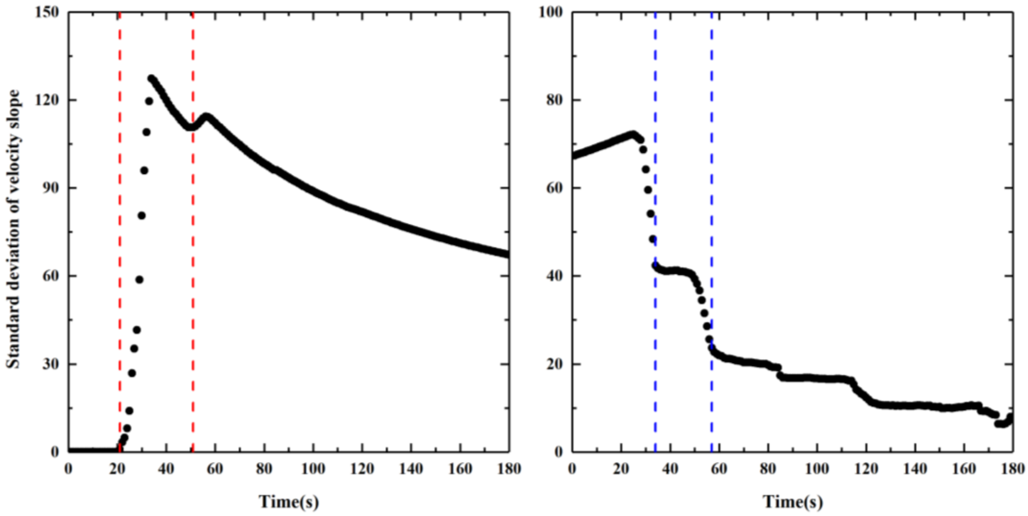

Fig. 4 – Variation of standard deviation of slopes of velocity time series subtracted by the linear slope of the regression model from (a) t = 0 to 20 s, (b) t = 160 – 180 s.

5. Comparison of the Displacement Time Series between the Previous and Proposed Approaches

Fig.5 shows the processed displacement time series assuming a single fling step following the past studies [2,3]. Fig.5a, 5b, and 5c show EW, NS, and UD component, respectively. The start and end times of the fling step are selected at 21 s and 57 s based on Figs.1, 3 and 4. The bracket duration with the threshold values of 50 gal suggested by [2] was not used because it returned a long time interval from 20 to 122 s duo to the small shaking at 115 s in Fig.1, and that is clearly incorrect because no strong shaking exist from 62 – 83 s and 90 – 110 s. The choice of the start and end times of baseline correction is subjective [3]. Fig.5 shows that the permanent displacements continuously increase from 21 s and 57 s for all directions even though the strong shaking does not exist between first and second ruptures from 36 to 43 s in Fig.2. This observation shows a clear limitation of the previous approach because it cannot consider the multiple fling steps in the strong motions.

Fig. 6 shows the displacement time series processed by the proposed approach assuming two fling steps in the ground motion. The first one occurs from 21 to 34 s and the second one from 50 to 57 s based on Figs.3 and 4. A small time window was also added from 83 to 85 s to remove the baseline errors at this interval which can be observed in Fig. 2 and Fig. 4(b). The results show that the permanent displacement increases within the two time-windows of the fling steps. These results are more reasonable than Fig.5 because no permanent displacement occurs during the time interval between 1st and 2nd rupture. Table 1 shows the resulted permanent displacement at the end of recordings assuming a single and two fling steps and the GPS co-seismic displacement. Compare to the GPS values, single fling step shows an exaggerated residual displacement both in EW and NS components, but two fling steps have a reduced displacement obviously. The proposed approach shows 52 - 78% smaller values than the past ones in horizontal components.

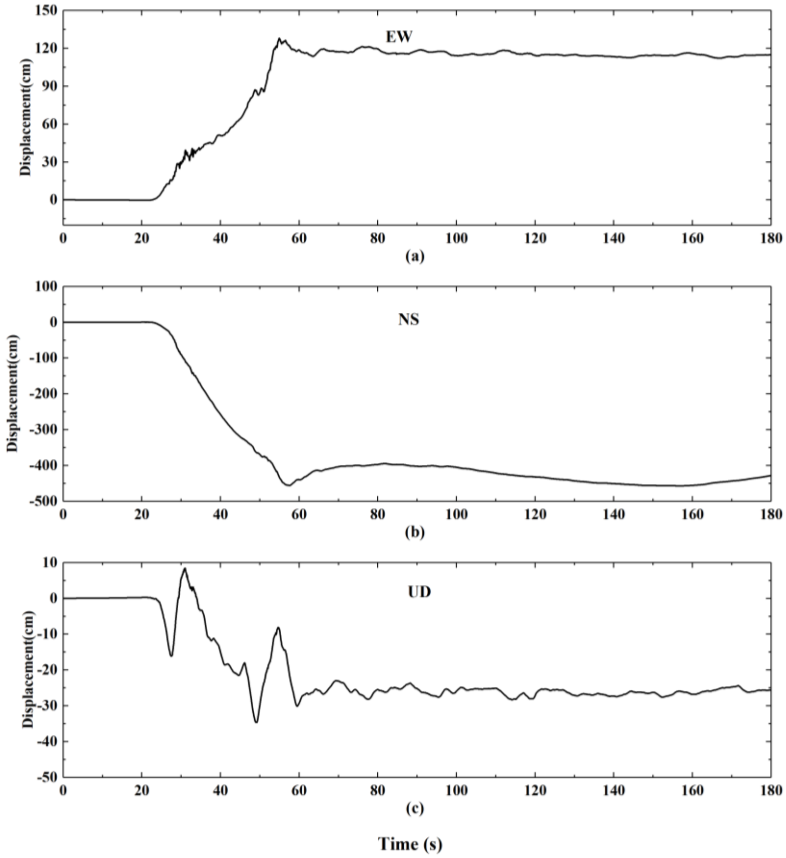

Fig.5 – Processed displacement time series assuming single fling step (a) EW, (b) NS, (c) UD component

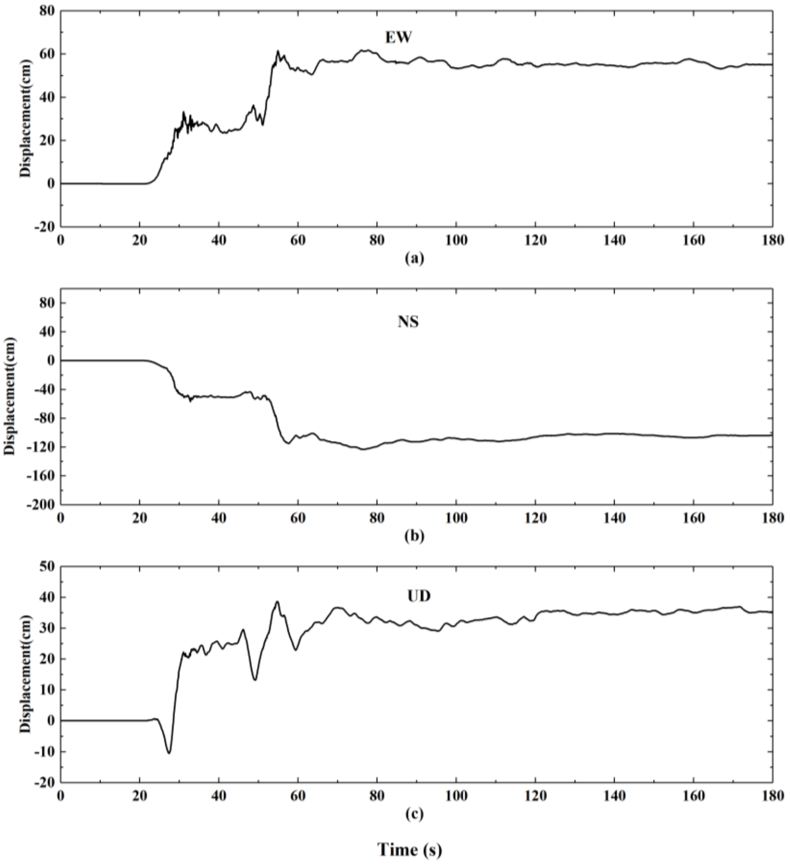

Fig. 6 – Processed displacement time series assuming multiple fling steps (a) EW, (b) NS, (c) UD component.

Table 1 – Permanent displacements assuming (a) a single fling step (b) two fling steps in acceleration time series recorded at 51WCW (c) GPS co-seismic displacement.

Ruptura	(a) Single fling step (cm)			(b) Two fling steps (cm)			(c) GPS co-seismic dispalcement (cm)		
	NS	EW	UD	NS	EW	UD	NS	EW	UD
1st	-428.1	114.7	-25.6	-50.4	27.5	24.4	-	-	-
2nd	-	-	-	-53.1	28.4	11.2	-	-	-
Total	-428.1	114.7	-25.6	-103.5	55.9	35.6	-37.4	64.0	-22.8

6. Conclusion

A new algorithm of baseline correction is proposed to extract the permanent displacement from strong motion time series. The approach is an expansion of the past studies [2,3], but can be applied when multiple fling steps exist in the strong motions. We analyzed the acceleration time series recorded at Station 51WCW during 2008 Ms8.0 Wenchuan Earthquake. The past studies showed that there were two major ruptures in Wenchuan Earthquake where the first rupture occurred at southern and the 2nd one occurred at northern segment of Beichuan falut, respectively.

The standard deviations of time series are computed using the residuals [14] and the residuals of slopes detrended by the linear fit of the velocity time series. The results show that there are two major offsets of standard deviations at which two major ruptures occurred. This observation indicates that the baseline correction is required by considering the multiple fling steps.

The recorded acceleration time series are processed assuming a single fling step in a strong motion [2,3]. The results show that the permanent displacement continuously increases during a time interval where the single fling step exits. This observation shows a clear limitation of the previous algorithm because the permanent displacement increases even though strong shaking does not exist between two ruptures. The time series are similarly processed assuming two fling steps using the proposed algorithm. The results show that the permanent displacement increases during the two fling steps, but does not increase between these, which is more reasonable than the previous results. Therefore, by using the strong motions recorded at Station 51WCW during 2008 Ms8.0 Wenchuan Earthquake, we clearly showed that the algorithm presented in the past studies have a technical limitation to process the time series with multiple fling steps, where the proposed algorithm resolved such a limitation.

7. Acknowledgements

Data for this study are provided by China Strong Motion Network Centre at Institute of Engineering Mechanics, China Earthquake Administration. The authors appreciate the support to access these data. The study is mainly supported by the National Key R&D Program of China (no. 2017YFC1500802), National Natural Science Foundation of China (nos. 51878632 and 51808514). The study is partially supported by the Abu Dhabi Department of Education and Knowledge (ADEK) through the 2018 ADEK Award for Research Excellence (AARE18-148). We appreciate these supports to present these results

8. References

[1] Ancheta TD, Darragh RB, Stewart JP, Seyhan E, Silva WJ, Chiou JBS, Wooddell KE, Graves RW, Kottke AR, Boore D.M., Kishida T., Donahue JL (2014): NGA-West 2 Database. *Earthquake Spectra*, **30** (3), 989-1005.

[2] Iwan WD, Moser, MA, Peng, CY (1985): Some observations of strong-motion earthquake measurement using a digital accelerograph. *Bulletin of Seismological Society of America*, **75** (5), 1225-1246.

[3] Boore DM (2001): Effect of Baseline Corrections on Displacements and Response Spectra for Several Recordings of the 1999 Chi-Chi, Taiwan, *Bulletin of Seismological Society of America*, **91** (5), 1199-1211.

[4] Kelson KI, Kang KH, William DP, Lee, CT, Cluff LS (2001): Representative Styles of Deformation along the Chelungpu Fault from the 1999 Chi-Chi (Taiwan) Earthquake: Geomorphic Characteristics and Responses of Man-Made Structures. Bulletin of the Seismological Society of America, **91** (5), 930–952.

[5] Ueng TS, Lin ML, Chen, MH (2001): Some Geotechnical Aspects of 1999 Chi-Chi, Taiwan Earthquake, *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics. 6.*, https://scholarsmine.mst.edu/icrageesd/04icrageesd/session14/6.

[6] Park SW, Ghasemi H, Shen J, Somerville PG, Yen WP, Yashinsky M. (2004): Simulation of the seismic performance of the Bolu Viaduct subjected to near-fault ground motions. Earthquake Engineering and Structural Dynamics, **33**,1249–1270.

[7] Zhang W, Kishida T, Bozorgnia Y, Taciroglu E (2020): Seismic Risk Assessment Methodology for Gas Pipeline Infrastructure Crossing Active Faults. *17th World Conference on Earthquake Engineering*, Sendai, Japan.

[8] Oettle NK, Bray JD, Dreger DS (2015): Dynamic effects of surface fault rupture interaction with structures. *Soil Dynamics and Earthquake Engineering*, **72,** 37–47.

[9] Burks LS, Baker JW (2016): A predictive model for fling-step in near-fault ground motions based on recordings and simulations. *Soil Dynamics and Earthquake Engineering*, **80**, 119–126.

[10] Grazier VM (2005): Effect of tilt on strong motion data processing. Soil Dynamics and Earthquake Engineering, **25**, 197–204.

[11] Boroschek RL, Legrand D (2006): Tilt Motion Effects on the Double-Time Integration of Linear Accelerometers: An Experimental Approach. *Bulletin of the Seismological Society of America*, **96**(6), 2072–2089.

[12] Pillet R, Virieux J (2007): The effects of seismic rotations on inertial sensors. *Geophysical Journal International*, **171**, 1314–1323.

[13] Wu YM, and Wu CF (2007): Approximate recovery of coseismic deformation from Taiwan strong-motion records, *Journal of Seismology*. **11**(2), 159–170.

[14] Akkar, S., and Boore, DM (2009): On baseline corrections and uncertainty in response spectra for baseline variations commonly encountered in digital accelerograph records, *Bull. Seism. Soc. Am.* **99**, 1671-1690.

[15] Chao WA, Wu YM, Zhao L. (2010): An automatic scheme for baseline correction of strong-motion records in coseismic deformation determination, *Journal of Seismology*. **14**(3), 495–504.

[16] Wang, R., B. Schurr, C. Milkereit, S. Zhigang, and J. Mingpei (2011): An improved automatic scheme for empirical baseline correction of digital strong-motion records, *Bull. Seismol. Soc. Am*. **101**, 2029–2044.

[17] D'Amico M, Felicetta C, Schiappapietra E, Pacor F, Gallovič F, Paolucci R, Puglia R, Lanzano G, Sgobba S, Luzi L 2018): Fling Effects from Near-Source Strong-Motion Records: Insights from the 2016 Mw 6.5 Norcia, Central Italy, Earthquake. *Seismological Research Letters*, **90**(2A), 659–671.

[18] Xie Junju, Wen Zengping, Gao Mengtan. (2013): Recovery of co-seismic deformation from strong motion records during the Wenchuan earthquake. *Acta Seismologica Sinica*, (3): 369-379.

[19] Hayes GP (2014): U.S. Geological Survey's National Earthquake Information Center https://earthquake.usgs.gov/earthquakes/eventpage/usp000g650/finite-fault?source=us&code=usp000g650 (last accessed 01/28/2020).

[20] Feng GC, Hetland EA, Ding XL, Li ZW, Feng LZ (2010): Coseismic fault slip of the 2008 Mw 7.9 Wenchuan earthquake estimated from InSAR and GPS measurements, *Geophysical Research Letters*, **37**, L01302.

[21] Xu C, Liu Y, Wen Y, Wang R (2010): Coseismic Slip Distribution of the 2008 Mw 7.9 Wenchuan Earthquake from Joint Inversion of GPS and InSAR Data. *Bulletin of the Seismological Society of America*, 100(5B), 2736–2749.

