Comparison of Coseismic Displacement Obtained from GEONET and Seismic Networks

Luis Moya[*], Fumio Yamazaki[†] and Wen Liu[‡]
Graduate School of Engineering
Chiba University Chiba 263-8522, Japan
[*]*lmoyah@chiba-u.jp*
[†]*fumio.yamazaki@faculty.chiba-u.jp*
[‡]*wen.liu@chiba-u.jp*

It is generally recognized that permanent displacements estimated by the double integration of acceleration records need a suitable baseline correction. Current baseline correction methods have been validated by comparing the displacements with those from the Global Positioning System (GPS) records nearby, but GPS stations that are sufficiently close to a strong-motion station are scarce. Because the M_w9.0 Tohoku-Oki earthquake produced geodetic displacements in a wide area and because dense strong-motion and GPS networks are available in Japan, we interpolated the displacements calculated from GPS records to estimate the permanent displacements at 508 strong-motion stations. The estimated results were used to evaluate uncertainties in permanent displacements obtained using two baseline correction methods, and results were found to be reliable only for KiK-net's borehole acceleration records. A new joint parameter search method for the surface and borehole records was further proposed, and reliable results were obtained for KiK-net's surface records.

Keywords: Coseismic displacement; strong motion; GPS

1. Introduction

Permanent displacements measured after earthquakes are currently used to estimate coseismic slip (crustal movement) distribution and moment magnitude and to issue tsunami early warning. Permanent displacements can be retrieved using different technologies such as those based on global navigation satellite systems (GNSSs), strong-motion records, and satellite synthetic aperture radar imagery. Geodetic methods using GNSSs such as the GPS are the most reliable technology to calculate permanent displacement, but in such methods, real-time monitoring is not possible so far. The kinematic precise-point-positioning (KPPP) technique requires the final precise orbit information and a high-rate 30-s satellite clock to achieve an accuracy level of a few centimeters [Zumberge et al., 1997]. However, those information are available only 12–18 days after an earthquake from the International GNSS Service. The kinematic differential positioning technique can be used to estimate the displacement of a receiver in real time, but its results are relative to a reference station. Thus, this technique cannot estimate the total displacement because the reference station is also in motion during strong earthquakes. Another approach is to estimate the static coordinates before and after an earthquake [Ozawa et al., 2011], but special attention is required during the selection of an epoch to ensure that early aftershocks are not considered.

Despite new efforts to obtain GPS records in real time [Colosimo et al., 2011; Branzanti et al., 2013; Liu et al., 2014; Niu and Xu, 2014], GPS observation stations are still rare compared to strong-motion seismic stations, which are found all around the world. Theoretically, displacement time history can be calculated from an acceleration record by numerical integration. However, in most cases, unphysical and meaningless displacement is obtained if baseline correction is not applied (Figure 1). In a standard procedure used in earthquake engineering, the effects of baseline shift are removed by applying a low-cut filter to an acceleration record, but the low-frequency contents of permanent displacement are also removed in this process. On the other hand, a more complex technique using symmetrical FFT technique has been proposed to calculate permanent displacement [Katukura et al., 1989; Hayashi et al., 1991].

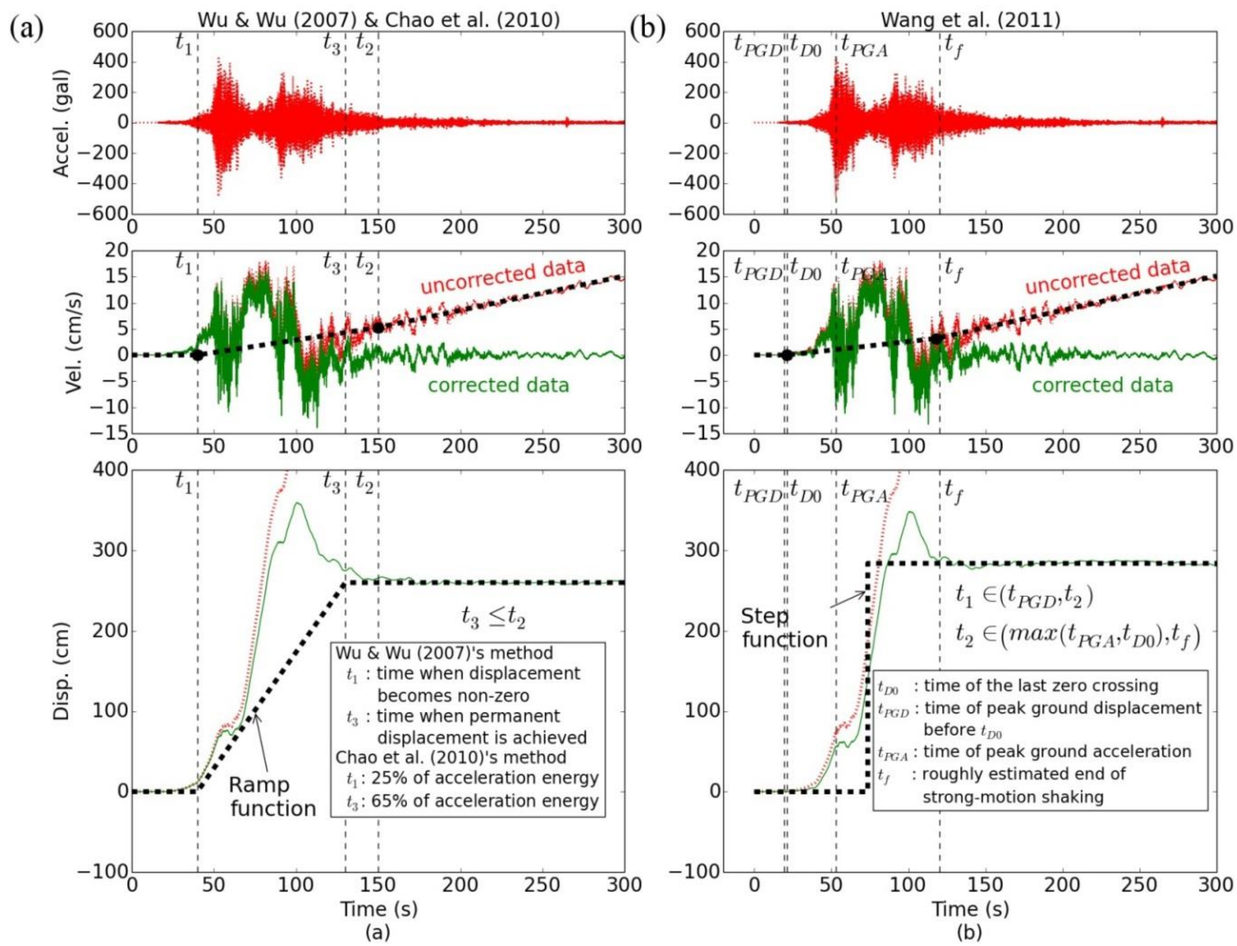

Figure 1. Scheme of the baseline correction method. (a) Wu and Wu (2007)'s method and Chao et al. (2010)'s method. (b) Wang et al. (2011).

Baseline shift is produced by several factors such as the hysteresis of transducers, tilting, and ground rotation [Iwan et al., 1985; Graizer, 2005; Graizer, 2006; Graizer, 2010], which are almost impossible to quantify. Thus, researchers adopted empirical approaches based on a trend observed in uncorrected velocity records and then proposed baseline correction methods [Graizer, 1979; Iwan et al., 1985; Wu and Wu, 2007; Wang et al., 2011]. These baseline correction methods were validated by comparing the results with GPS measurements [Boore, 2001; Wu and Wu, 2007; Wang et al., 2013]. For a reasonable comparison, the distance between GPS and seismic stations must be sufficiently close to consider that both stations report the same permanent displacement due to crustal movement. Boore [2001] compared four pairs of (strong-motion and GPS) stations whose distances were less than 6.5 km, Wu and Wu [2007] used 16 pairs with distances less than 4 km, and Wang et al. [2013] used 15 pairs with distances less than 4 km. Because of the selection of close distances, the number of available station pairs was significantly reduced for evaluating the performance of baseline correction methods.

The M_w9.0 Tohoku-Oki earthquake on March 11, 2011 generated large crustal movement in the northeastern half of Japan. From K-NET and KiK-net, the two biggest strong-motion networks in Japan, a total of 1226 stations recorded the strong acceleration time histories from the main shock. Permanent displacements with maximums of 5.3 m to the horizontal (southeast) and 1.2 m to the vertical (downward) components were observed from GPS stations [Ozawa et al., 2011; Hashimoto, 2013]. In this paper, we focus on the evaluation of the current baseline correction methods for recorded ground motion to recover coseismic displacements from the 2011 Tohoku-Oki earthquake.

2. Summary of baseline correction methods

As mentioned before, velocity and displacement time histories can be obtained by the single and double numerical integration of acceleration record, respectively. However, in most cases, the integration process produces unphysical results, as shown in the example in Figure 1. This effect is due to a slight shift of the baseline in the acceleration record, whose amplitude varies with time. One of the first methods to calculate displacement time history was proposed by Graizer [1979], where the baseline shift in the velocity time history is modeled by a 3-degree polinomyal. The polinomyal is calculated by least-squares fitting of the pre- and post-event of the records. Later, Graizer [2005] pointed out that polynomials up to fifth degrees were used for baseline correction in real cases. On the other hand, several researchers studying this problem estimated two constant baseline shifts: one for the strong shaking part, and the other for the latter shaking part. The initial pre-shaking part is set to be zero mean as a standard procedure, and thus, the effect of baseline shift is not observed in the initial part.

$$v_m(t) = v_{m0} + a_m t \quad (t_1 \le t < t_2) \tag{1a}$$

$$v_f(t) = v_{f0} + a_f t \quad (t_2 \le t) \tag{1b}$$

$$v_m(t_2) = v_f(t_2) \tag{1c}$$

where a_m denotes the shift between times t_1 and t_2, and a_f denotes the shift from t_2 to the end of the record. The important task in baseline correction methods is to remove the trend of v_m and v_f from the velocity record; then, the corrected displacement can be calculated. Note that no procedure exists that can recover the actual strong motion from an acceleration record and that the adjective “corrected” is used in this paper to represent the result obtained after the linear trend has been removed. The coefficients v_{f0} and a_f in

Eq. (1b) can be calculated accurately by a least-squares fitting method. However, v_m depends on the time parameters t_1 and t_2, and thus, its calculation is not straightforward. In the following paragraphs, we summarize the current methods used to estimate the time parameters t_1 and t_2.

Iwan et al. [1985] performed one of the first researches on the background noise of a digital strong-motion recorder, in which the effect of a baseline shift was included. They attributed the baseline shift to be the result of electrical hysteresis of the transducer system and proposed two different approaches to estimate the time parameters. In the first approach, the times of the first and last occurrences of acceleration greater than 50 cm/s^2 are selected as t_1 and t_2. In the second approach, t_1 is selected as the first significant acceleration pulse and then t_2 is selected as the time that minimizes the final displacement.

Boore [2001] studied the effect of baseline correction on the permanent displacement and compared it with the displacement observed by a GPS station, which is located near the accelerometer station. He found that the estimation of baseline shift using the two constant values (a_m and a_f) is sufficiently accurate, but that better criteria to select the time parameters (t_1 and t_2) are necessary. Wu and Wu [2007], pointed out that the corrected displacement history takes the shape of a ramp function. Therefore, t_1 is estimated as the time when the displacement record moves away from the zero line, but not greater than the time at which acceleration first exceeds 50 cm/s^2, and added a third time parameter t_3, which represents the time when the ground has just reached the permanent (static) displacement. The parameter t_2 is located between t_3 and the end of the record, and it must produce the maximum value of the flatness indicator, f, which is defined as follows:

$$f = \frac{|r|}{|b| \cdot V} \tag{2}$$

where r is the linear correlation coefficient, b is the slope of the linear least-squares fitting, and V is the variance. The flatness indicator is calculated from t_3 to the end of the record, and the time parameters are chosen by a recursive process. To simplify the recursive process and to automate the procedure, Chao et al. [2010] suggested that t_1 can be located at a ratio of 25% in the cumulated acceleration energy, and t_3 at 65%.

Wang et al. [2011] proposed a method in which t_1 and t_2 are free parameters located in the following interval:

$$t_{PGD} \le t_1 < t_2 \tag{3a}$$

$$max(t_{D0}, t_{PGA}) \le t_2 < t_f \tag{3b}$$

where t_{D0} is the time of the last zero crossing of the uncorrected displacement, t_{PGD} is the time of the peak ground displacement before time t_{D0}, t_{PGA} is the time of the peak ground acceleration, and t_f is an estimated end of strong ground shaking. They chose the time parameters through an iterative process to ensure that the corrected displacement best fits a step function.

3. Strong-motion and GPS networks in Japan

After the 1995 Hyogoken-Nanbu (Kobe) earthquake, the National Research Institute for Earth Science and Disaster Prevention (NIED) constructed two strong-motion networks: the Kyoshin Network (K-NET) and the Kiban-Kyoshin Network (KiK-net) [Aoi et al., 2004]. The K-NET consists of more than 1,000 stations installed on the ground surface which covers Japan's territory uniformly, and the stations are located mostly in public offices, schools, and parks. The KiK-net consists of approximately 700 stations, each of which is equipped with two accelerometers: one on the ground surface, and the other in the borehole at the bedrock level. K-NET stations are located in inhabited (urban to suburban) areas, whereas KiK-net stations are laid on stiff-soil or rock sites, which are generally less populated.

The development of the geodetic network in Japan began in 1994 [Sagiya, 2004] using signals from the GPS of USA. By introducing several technical advancements, the new GPS Earth Observation Network System (GEONET) was built in 2004, which added real-time capability with 1,200 stations at intervals of approximately 20 km [Yamagiwa et al., 2006]. The network, operated by the Geospatial Information Authority of Japan (GSI), was renamed the GNSS Earth Observation Network System (GEONET) because signals from other new GNSSs such as the Russian GLONASS and Japanese QZSS became available and could be received by the system.

4. Distribution of crustal movement obtained from GEONET data for the Tohoku-oki earthquake

Baseline correction methods have been examined by comparing the final corrected displacement with that of the nearest GPS station [Boore, 2001; Wu and Wu, 2007; Wang et al., 2013]. However, this approach cannot be widely used because only few strong-motion stations are located sufficiently close to GPS stations. Considering this fact, we apply the kriging interpolation method [Cressie, 1991] to the GEONET data for the 2011 Tohoku-Oki earthquake to estimate the crustal movement at all the K-NET and KiK-net stations. Then, the corrected displacements obtained from acceleration records after applying baseline correction are compared with the estimated GPS displacements.

Using the kriging method, the displacements recorded by the GEONET stations were interpolated to estimate the distribution of crustal movement at a specific location s_0 by the following equation:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{4}$$

where $Z(s_i)$ denotes the displacement measured by a GEONET station located at s_i, $\hat{Z}(s_0)$ is the predicted displacement at a location s_0, λ_i is the unknown weight factor for the measured value $Z(s_i)$, and N is the number of GEONET stations used in the interpolation. The weight factors λ_i*'s* are determined from a mathematical model fitted from the experimental semivariogram, and their summation value is 1.0.

Figure 2 shows the results of kriging interpolation for the permanent displacement produced by the 2011 Tohoku-Oki earthquake. The displacements at the GEONET stations were calculated from the difference between the station’s coordinates on March 10, 2011 and March 12, 2011; these coordinates were provided by the GSI. The arrows indicate the GEONET's data, and the shades indicate the displacement distribution by kriging interpolation. Twelve neighboring GEONET data values were used for each prediction point. The accuracy of the prediction was assessed by removing two GEONET stations (0546 and 0937) and using the remaining GEONET data to predict the values at the removed stations. The results of this examination are listed in Table 1. Because the crustal movement in the event extended to the wide area rather smoothly and the GEONET stations were deployed rather densely, the maximum error in the horizontal components was only 4 cm (1.6%) and that in the vertical components was 3 cm (7.3%), which is observed in the station 0546.

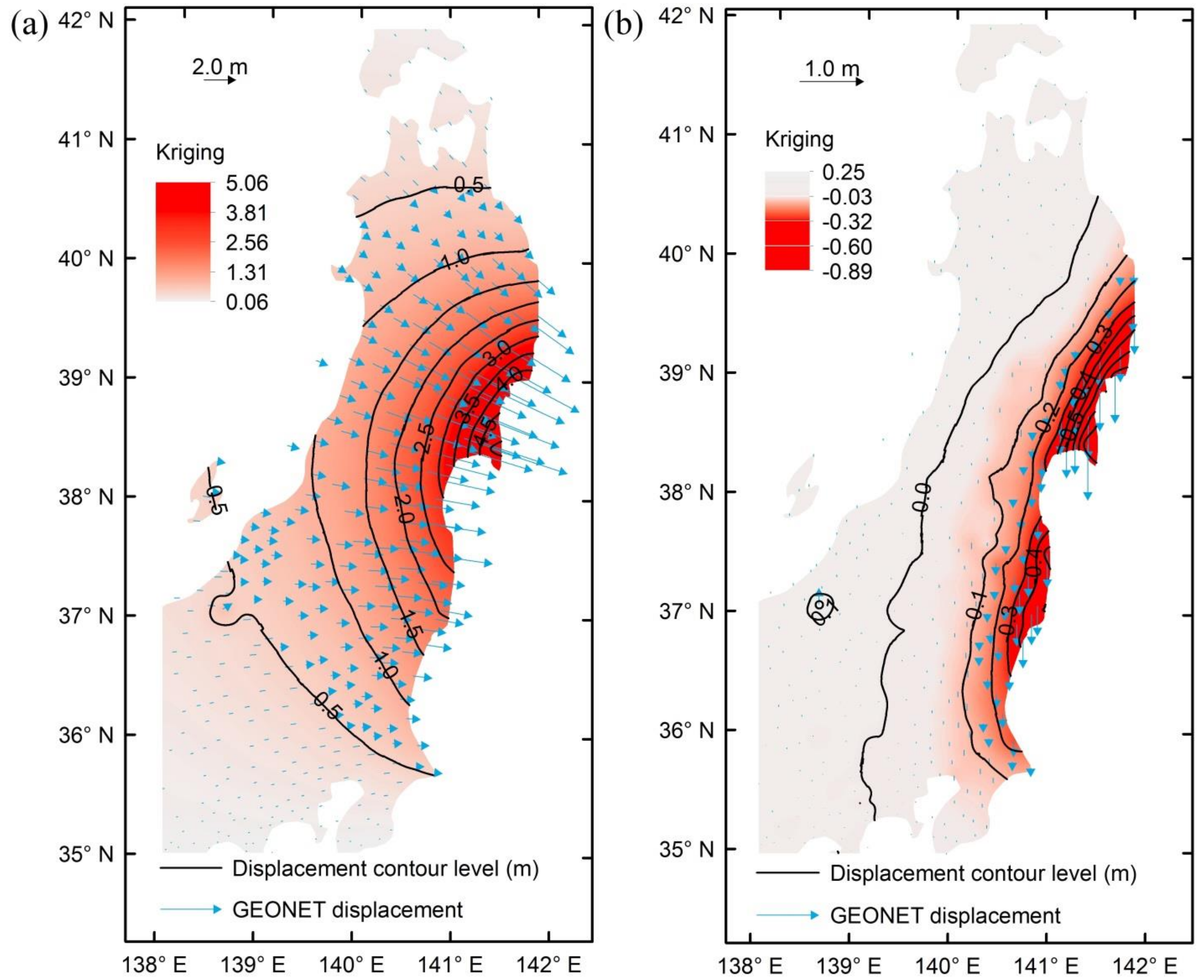

Figure 2. Spatial distribution of permanent displacements obtained from GEONET by using kriging interpolation. (a) Horizontal component and (b) vertical component.

Table 1. Comparison between displacements obtained from GPS and kriging interpolation.

Stations	East-West component			North-South component			Up-Down component		
	GPS (m)	Kriging (m)	Error (%)	GPS (m)	Kriging (m)	Error (%)	GPS (m)	Kriging (m)	Error (%)
0546	2.97	3.01	1.6	-1.67	-1.68	0.6	-0.41	-0.44	7.3
0937	1.24	1.23	0.5	-0.10	-0.10	2.0	-0.04	-0.04	2.4

Note: The error values were calculated using four-digit numbers.

5. Permanent displacements obtained from acceleration records

Baseline correction was applied to all the strong ground motion records from K-NET and KiK-net whose stations were located in the study area shown in Figure 2. The records from a total of 310 K-NET stations and 198 KiK-net stations were processed. Considering that KiK-net stations have two accelerometers (at the bedrock and surface) and each accelerometer provides three components, a total of 2,118 records were used. Owing to the large number of records, this study adopted the methods proposed by Chao et al. [2010] and Wang et al. [2011] because these methods were based on an automatic scheme. For the sake of brevity, the baseline correction methods of Chao et al. [2010] and Wang et al. [2011] are hereafter referred to as Chao's method and Wang's method, respectively.

Additional details related to Wang's method are provided below. Eq. (3b) implies that t_{D0} is smaller than t_f, but some records showed the opposite result. For such cases, we only inverted the order of the equation ($t_f \leq t_2 < max(t_{D0}, t_{PGA})$) to avoid major modifications in the procedure. Moreover, during the iterative process, the variance between the corrected displacement and its fitted step function was used to judge the best time parameters.

The coseismic displacements obtained from acceleration records were compared with the results obtained by kriging of the GEONET data (Figure 3). Because GPS displacements guarantee an accuracy of a few centimeters and the 2011 Tohoku-Oki earthquake produced displacements of a few meters, we considered the results from kriging to be the truth data. It is observed that the results for horizontal displacements from the acceleration records at the bedrock agree reasonably well with those from kriging. In contrast, horizontal displacements from the acceleration records at the surface are dispersed without a clear trend. The poor results for K-Net and KiK-net surface records were also observed by Hirai and Fukuwa [2012] and Wang et al. [2013]. They attributed this uncertainty to the soil conditions of the seismic stations, where nonlinear baseline shifts were possibly produced. The vertical component of permanent displacements from acceleration records, either bedrock or surface, show large differences from that of GEONET because the displacements are small, and even the horizontal components show high dispersion at these level of amplitudes.

To quantitatively compare the results, least-squares regression lines assuming a constant standard deviation were obtained and are shown in Figure 3. The results from the KiK-net bedrock are focused upon because only these results show linear trends; no major difference is observed in the slope of the linear trend, which is close to one, with the exception of the vertical component results. In addition, the standard deviation obtained from Wang's method is lower than that from Chao's method for all components. The average of the standard deviation from the three components is 36.7 cm and 98.0 cm for Wang's method and Chao's method, respectively. These results suggest that Wang's method shows better accuracy.

A closer look at the results shows that better accuracy is achieved when the permanent displacement is large. This trend is clearly observed in Figure 4, where the vertical axes shows the ratio of the results calculated using Wang's method to the results calculated from the GPS, and the horizontal axes shows the lateral displacement from GPS. The accuracies of both the amplitude of the horizontal component (the resultant of two directions) and its direction (the angle from the north) are shown in Figure 4. Strong-motion stations with permanent displacements greater than 1 m show almost uniform variability with the exception of a few points. The average ratio for these stations is 0.95±0.12 for the amplitude and 1.04±0.31 for the azimuth. In contrast, stations with permanent displacements less than 1 m show results with high dispersion. On the other hand, it is well understood that the largest displacements are located near the source; therefore, Figure 4 provides insight into how the maximum distance between the station and the source can be used as a threshold to filter poor results. However, data from several events with different magnitudes are necessary for this purpose, which is outside of the scope of this research.

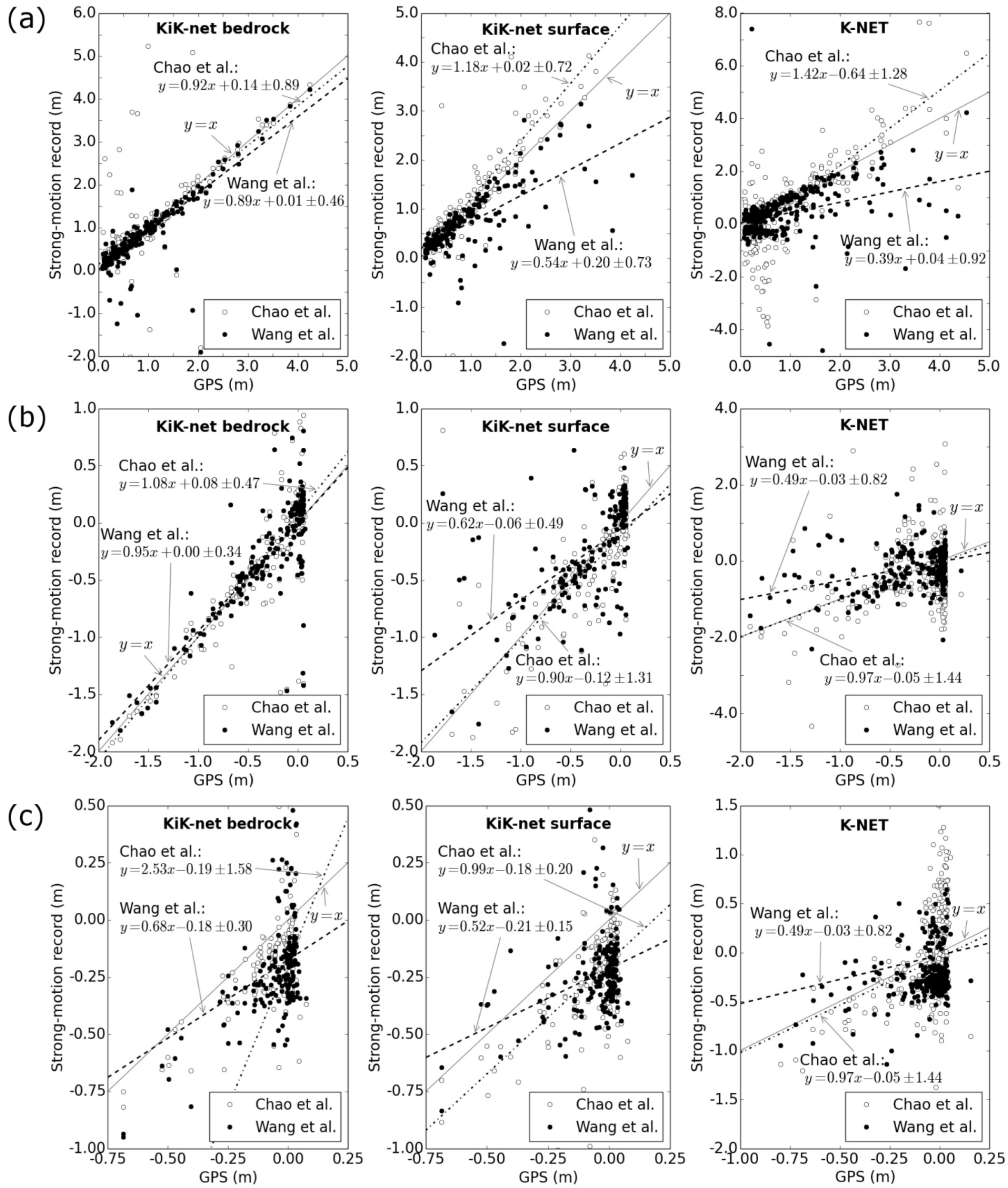

Figure 3. Comparison between permanent displacement obtained from kriging of GEONET data and from acceleration records for (a) EW component, (b) NS component, and (c) UD component. The symbols x and y are the abscissas and ordinates, respectively. The linear equations calculated from least-squared regression are expressed in meters.

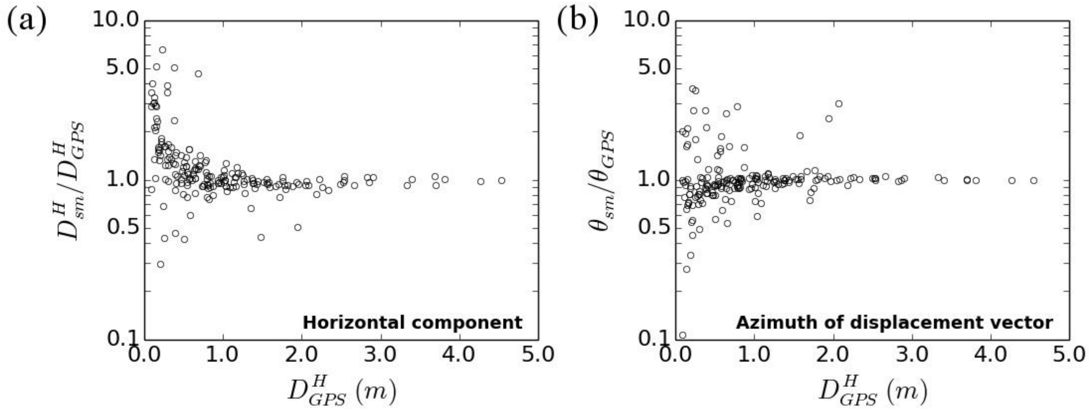

Figure 4. Ratio of coseismic displacements calculated from Wang et al. (2011)'s method and the one obtained from the interpolation of GPS data for the KiK-net bedrock sites. (a) Horizontal component and (b) displacement azimuth.

6. Joint parameter search for KiK-net stations

A new approach to select the most suitable baseline shift for KiK-net stations is proposed. The baseline correction methods used in previous studies determine the time parameters in such a way that the corrected displacement best fits some shapes such as a ramp function [Wu and Wu, 2007; Chao et al., 2010] or a step function [Wang et al., 2011]. Furthermore, the time parameters are restricted in some intervals under certain criteria (e.g., Eq. (2) and (3)).

Because each KiK-net station has two accelerometers (at the bedrock and surface levels), this advantage can be used to estimate the coseismic displacement without the necessity of restraining the time parameters or fitting the results to a shape function. Considering that in a large earthquake, the residual soil deformation at the ground surface is much smaller than that of the crustal movement, the permanent displacement should be almost the same at the surface and bedrock. On the other hand, each accelerometer is affected by the baseline shift in a different manner because the factors producing the shift, such as the acceleration level and confinement condition of the sensor, have different values for each shift.

We introduce the assumption that the corrected displacements obtained from the surface and bedrock records are equal or very close to each other and use this property to estimate the time parameters for both records. Note that although the displacements are very similar, the time parameters are not equal for both records; thus, an extra index (*b* for bedrock and *s* for surface) is required to differentiate between them. To control the similarities, we use the sum of squares of the differences between the corrected displacements at the bedrock and surface as follows:

$$S\left(t_1^b, t_2^b, t_1^s, t_2^s\right) = \sum_{j=1}^{N} \left(D_j^b\left(t_1^b, t_2^b\right) - D_j^s\left(t_1^s, t_2^s\right)\right)^2 \tag{5}$$

where j denotes the position of a control point in the record, N is the number of control points, and $D_j^i\left(t_1^i, t_2^i\right)$ is the corrected displacement obtained at the control point j using the time parameters t_1^i, t_2^i. Eq. (5) is considered to be pseudo-variance because if the number of control points is equal to the number of data points in the record, the pseudo-variance will be equal to N times the variance. Finally, the objective of our proposal is to find a set of time parameters (t_1^b, t_2^b, t_1^s and t_2^s) that will reduce the pseudo-variance to its minimum value.

The minimum value of S can be calculated by an optimization process or a suitable grid search approach. However, these methods require repetitive operations that would involve large computational efforts because the pseudo-variance is a fourth-dimensional function. To reduce the computational efforts, it is recommended that the corrected displacement be calculated directly from its mathematical meaning and not by a numerical integration procedure. Here, the corrected displacement at a control point represents the difference between the uncorrected displacement and the integration of the linear trend observed in the velocity time history. Therefore, the corrected displacement is expressed as

$$D_j(t_1,t_2)=\begin{cases} d_j, & t_j<t_1 \\ d_j-\int_{t_1}^{t_j}(a_m t+v_{m0})dt, & t_1\le t_j<t_2 \\ d_j-\int_{t_1}^{t_2}(a_m t+v_{m0})dt-\int_{t_2}^{t_j}(a_f t+v_{f0})dt, & t_2\le t_j \end{cases} \quad (6)$$

where d_j is the uncorrected displacement at time t_j. If the corrected displacement, D_j, is calculated by numerical integration, a process of adding up the value of the integrand at a sequence of all abscissas before a control point will be necessary. On the other hand, Eq. (6) implies that the uncorrected displacement, d_j, needs to be computed only once using any numerical integration procedure.

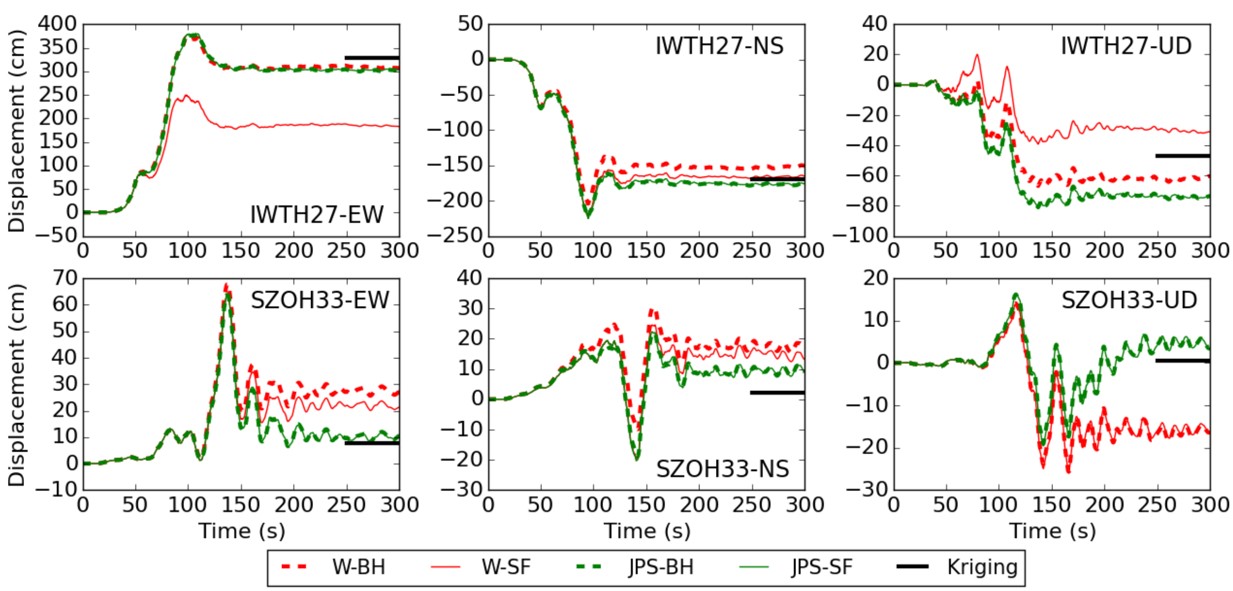

Figure 5. Corrected displacement record from Wang et al. (2011)'s method and joint parameter search for the KiK-net IWTH27 and SZOH33 stations (W: Wang et al. (2011); JPS: Joint parameter search; BH: borehole accelerometer; SF: surface accelerometer).

Figure 5 shows a comparison between displacement time histories obtained from our joint parameter search method and Wang's method. The records used belong to the KiK-net IWTH27 and SZOH33 stations. The displacement obtained by interpolation of GPS data is also shown in the figure. On the basis of our proposal, the time parameters were found using a grid search approach and the pseudo-variance was calculated using 50 control points uniformly distributed over the record (every 6 s). As pointed out previously, Wang's method yields different values for the records recorded at the surface and bedrock, with the one at the bedrock being more accurate. On the other hand, when both records are combined on the basis of our proposal, the same level of accuracy is obtained for both records. Figure 6 shows the permanent displacements produced by the Tohoku-Oki earthquake, obtained from all the stations located in our study area using the joint parameter search method, Wang's method, and the interpolation from GPS data. The figure clearly indicates that our method produces better results for the KiK-net surface records than the existing methods. This implies that removing the linear trend from the velocity record is a good practice for surface records as well. This result demonstrates that it is possible to obtain better time parameters t_1 and t_2 for KiK-net surface accelerometers than the ones obtained using previous methods.

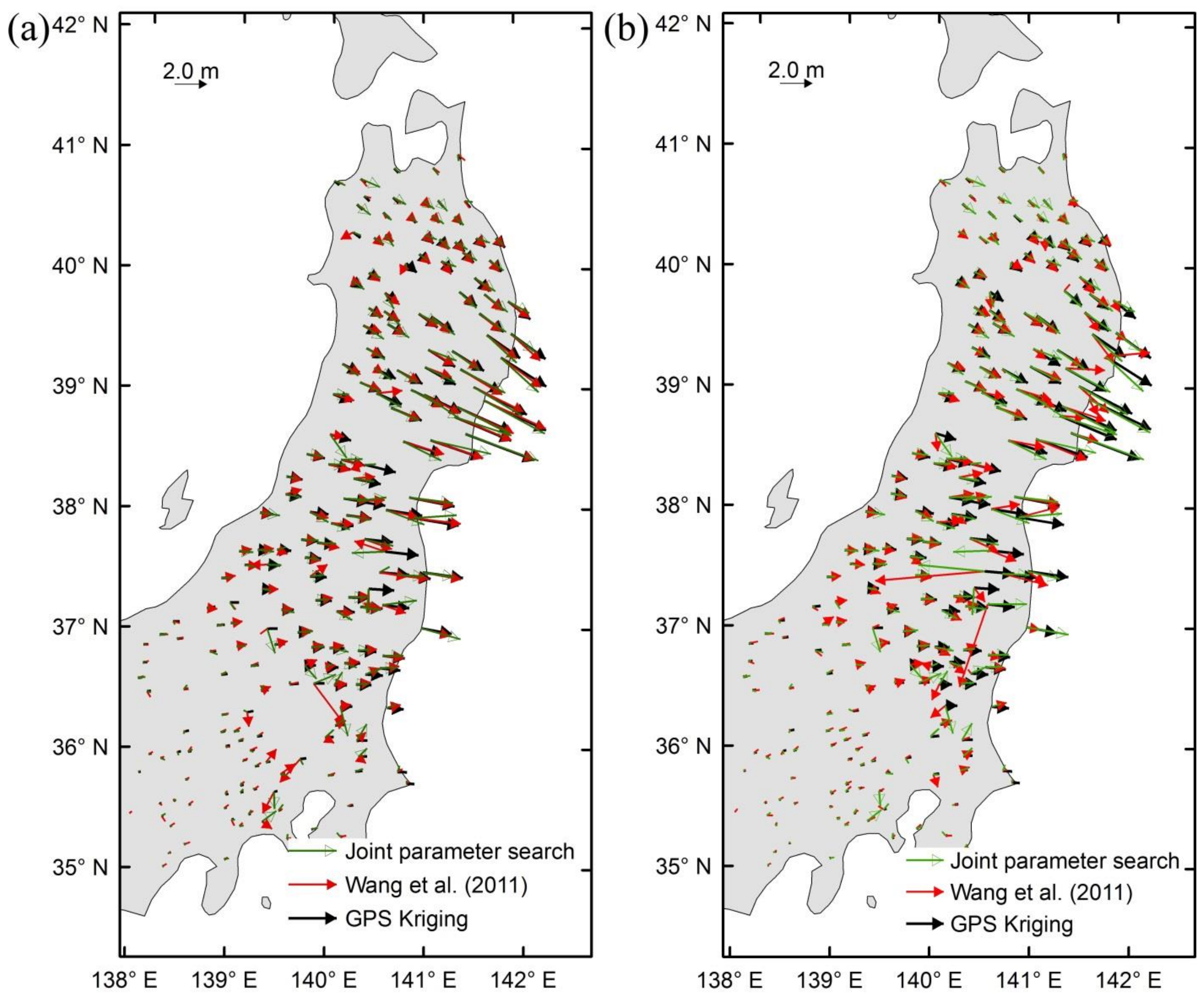

Figure 6. Distribution of permanent displacement after the Tohoku-Oki earthquake obtained from the interpolation of GPS data, Wang's method, and the joint parameter method. (a) KiK-net bedrock and (b) KiK-net surface.

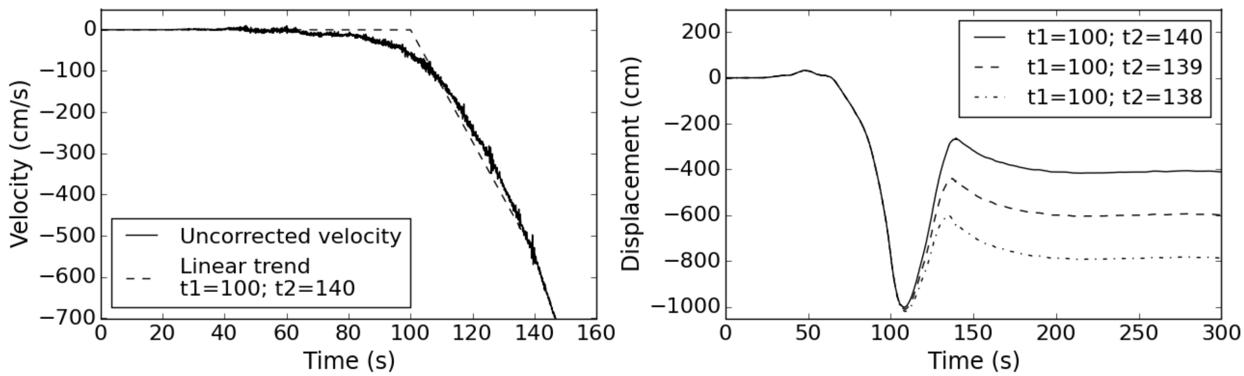

Figure 7. Uncorrected velocity and corrected displacement using three pairs of time parameters for the KiK-net FKSH18 station

However, at some locations, the results are different between bedrock and surface, with the main reason being a non-linear trend observed in the baseline shift, which cannot be removed properly by a bi-linear correction. As an example, Figure 7 shows the corrected displacement obtained from three pairs of time parameters for the station FKSH18, in which t_1 is constant (100 s) and t_2: 138 s, 139 s, and 140 s. It is observed that an increment of 1 second in t_2 produce an increment of 2 meters in the final displacement. This high sensitivity to the time parameters makes it difficult to obtain very similar results between bedrock and surface when using our method.

Figure 8 shows a scatter plot comparison between permanent displacements obtained from the kriging of GEONET data and using the joint parameter search method. The least-squares regression lines obtained from the results have a slope close to one and indicate significant improvements in the standard deviation for the KiK-net surface records compared with the results shown in Figure 3. Hence, the results shown in Figure 6b are confirmed.

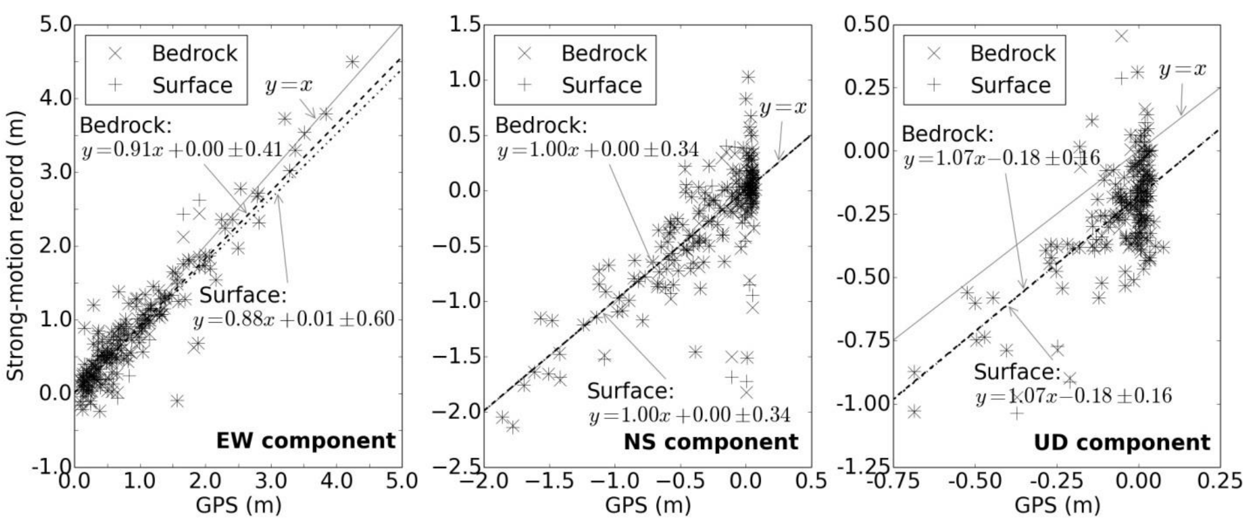

Figure 8. Comparison of permanent displacements obtained from the joint parameter search method and from the interpolation of GPS data. The symbols *x* and *y* are the abscissas and ordinates, respectively. The linear equations calculated from least-squared regression are expressed in meters.

The corrected displacement time history was evaluated by comparing it with the 30-s GPS displacements obtained from a nearby GEONET station for 12 cases; the separation between the KiK-net and GEONET stations was within approximately 5 km. The GPS displacements were calculated by applying the KPPP technique using the RTKLIB software; final precise orbit information of every 15 min, 30-s satellite clock, and absolute antenna phase center variation (PCV) models were used. The elevation cut-off angle for the GPS satellites was 10°. Figure 9 compares the displacement time histories from the joint parameter search method and GEONET stations. Good agreement is found between the KiK-net and GEONET records although slight differences are observed after the permanent displacement is achieved. However, the most remarkable characteristic is that both the KiK-net surface and bedrock records show the same level of accuracy.

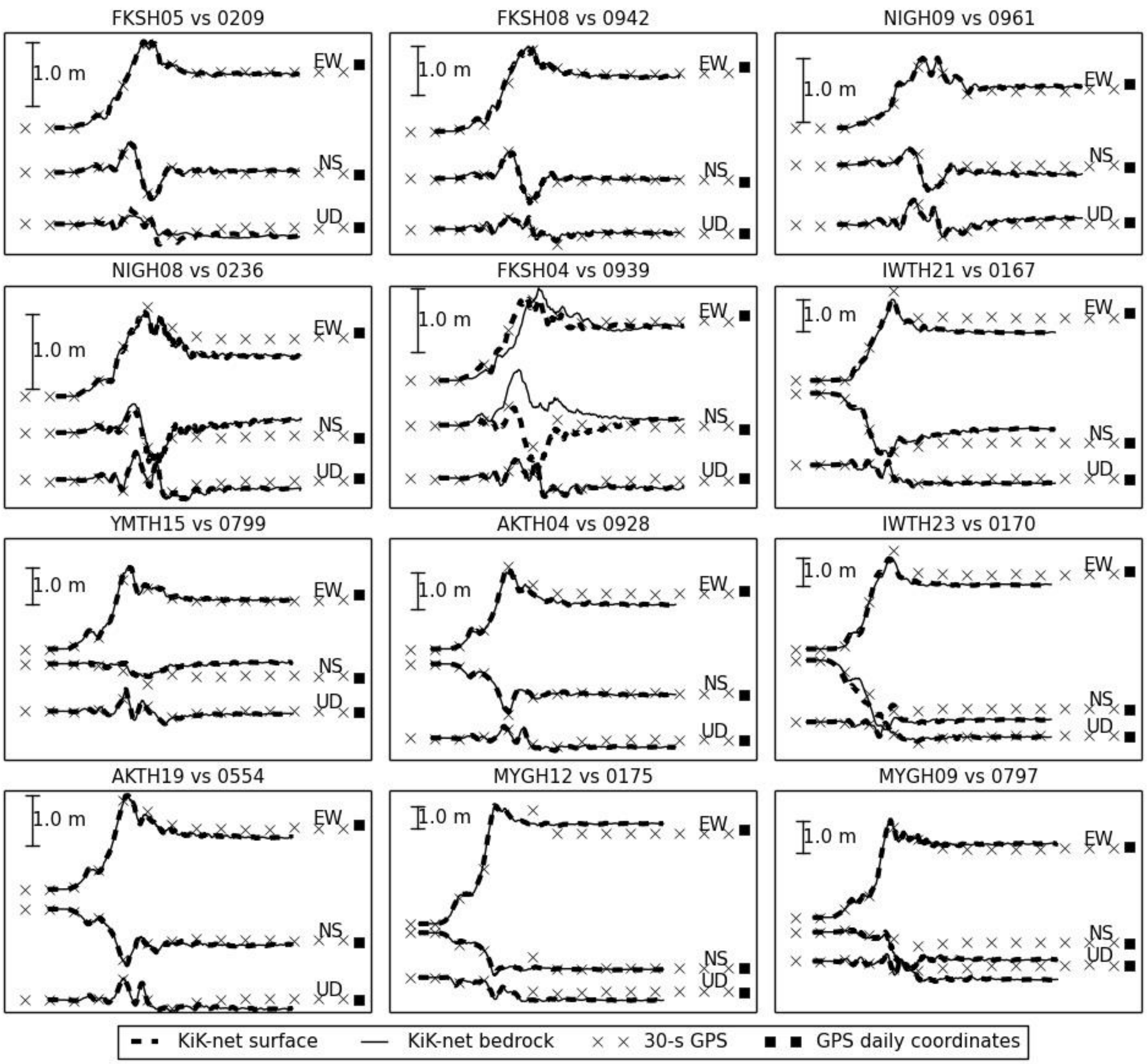

Figure 9. 30-s GPS displacement (symbol x) and displacement time histories from the joint parameter search method at the borehole (solid line) and the surface (dashed line).

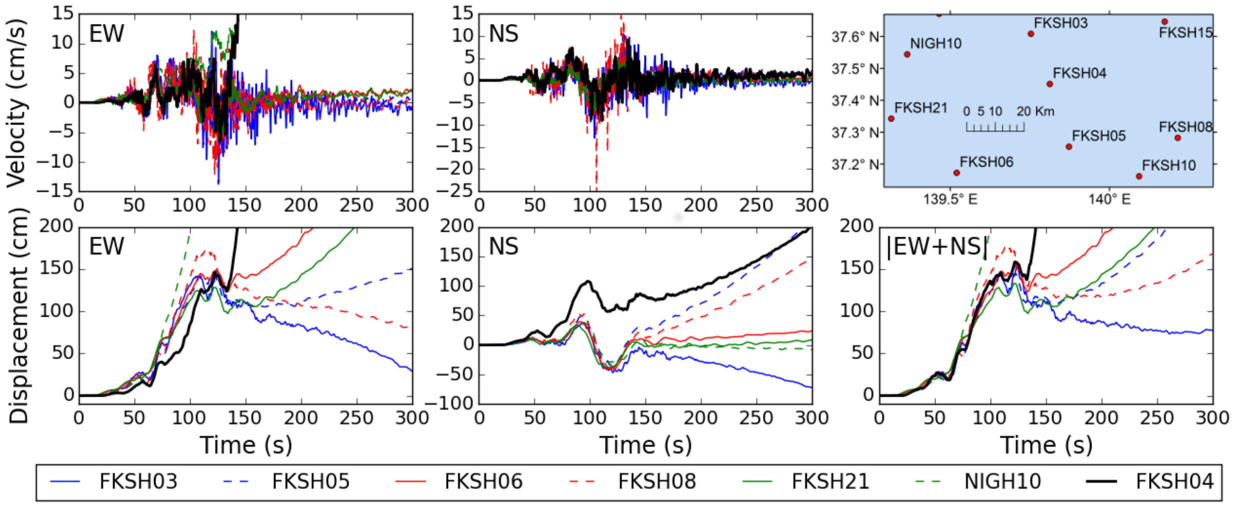

Figure 10. Uncorrected records of KiK-net station FKSH04 and stations nearby.

Significant difference is observed between the FKSH04 (KiK-net) station at the bedrock and the 0939 (GEONET) station. Direct evidence of error in the installation angle was found for FKSH04 station. Figure 10 shows the uncorrected velocity and displacement of the east-west and north-south component of FKSH04 and stations nearby. Besides, the total horizontal component is shown as well. From the uncorrected velocity, it can be assumed that in the early part of the record the baseline shift has not affected significantly the record. Thus, evaluating the first 100 seconds and considering the low spatial variation of coseismic displacement during the Tohoku earthquake, it can be observed that the displacement time history of FKSH04 station is lower than the other stations in the east-west(EW) component, and greater in the north-south (NS) component. However, the total horizontal displacement (|EW+NS|) is very close to most of the stations. This anomaly is due to the effect of the orientation error of the three-component accelerometer about the vertical axis. However, even in this case, using our approach the final permanent displacements are very close to that from GEONET.

As observed in Figure 5, when the permanent displacement is greater than the transient wave, the results using only records at bedrock are slightly more accurate. However, in several cases when the permanent displacement is lower than the transient wave, our results are closer to that of GEONET. This tradeoff is reflected in the slope and standard deviation of the least-squares regression lines calculated from Wang's method (Figure 3) and our method (Figure 8), which are very close. Because the current methods can reproduce similar results as those using only records at the bedrock, it might seem that the proposed method does not provide any additional information related to permanent displacement distribution. However, the proposed method is useful in three aspects. First, we still estimate the baseline shift as two constant values: during the main shaking part and at the later part. This means that the only difference among the methods is the method of estimating the time parameters. Hence, we infer that a linear baseline shift is also sufficient for obtaining results using the records at the surface, and the poor results obtained by using the previous methods are not mainly because of nonlinear baseline shifts, as was suggested in the previous studies. Second, although the proposed method does not provide additional information on permanent displacement, the response time history at the surface obtained using our method can be useful in other fields (e.g. earthquake engineering). As an example, the velocity time history is required to extract multiple pulses from ground motion by using wavelet analysis [Lu and Panagiotou, 2014], which is of interest to researchers studying the structural response of tall structures. And the last but not least, we believe that, since Wang et al. (2011)'s method and our approach are of an empirical nature, having results from our method would be supportive.

7. Conclusions

In this study, the effect of baseline shift in acceleration records on the estimation of permanent displacements was evaluated. For this purpose, a large amount of strong-motion data recorded by KiK-net and K-NET during the M_w9.0 Tohoku-Oki earthquake was used. Two automatic baseline correction methods proposed by Chao et al. [2010] and Wang et al. [2011] were selected to remove the effects of baseline shift and estimate the permanent displacement. The results were compared with a more accurate displacement obtained from the kriging interpolation of GEONET data. The results showed that the current baseline correction methods could not obtain reliable permanent displacements for acceleration records at the ground surface. In contrast, reasonable results were found for acceleration records at the bedrock: Wang's method yielded the best results with a standard deviation of 46 cm, 34 cm, and 30 cm for the EW, NS, and UD components, respectively. Such a difference between the results from records at the surface and bedrock was also observed by Hirai and Fukuwa [2012] and Wang et al. [2013]. This is a disadvantage because most strong-motion accelerometers are located on the ground surface. In addition, high precision in amplitude and orientation has been observed in stations that develop large permanent displacements; the accuracy decreases as the permanent displacement reduces. This observation suggests that a minimum distance between the source and the strong-motion station can be used as a threshold to filter poor results.

A method to remove the effects of the baseline shift was developed by employing a joint parameter search for each KiK-net station with surface and borehole accelerometers. Using this method, a remarkable improvement was observed in the results for the records at the surface. However, our method has a limitation in that it requires the use of two accelerometers (at the bedrock and surface) deployed at the same site. The results of the joint parameter search method show that the time parameters obtained using previous methods can be improved and that the poor results at the surface are not mainly due to nonlinear baseline shifts.

8. Data and Resources

The KiK-net and K-NET data used in this study were provided by the National Research Institute for Earth Science and Disaster Prevention (NIED) from www.kyoshin.bosai.go.jp (last accessed December 2014). The GEONET data were provided by the Geospatial Information Authority of Japan (GSI) from ftp://terras.gsi.go.jp/data/ (last accessed December 2014). The open source program RTKLIB was downloaded from www.rtklib.com (last accessed December 2014).

References

Aoi, S., Kunugi, T., and Fujiwara, H., [2004]. “Strong-motion seismograph network operated by NIED: K-NET and KiK-net”, *Journal of JAEE*, Vol. 4, No. 3, 65-74.

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.

Branzanti, M., Colosimo, G., Crespi, M., and Mazzoni, A., [2013]. “GPS near-real-time coseismic displacements for the Great Tohoku-oki Earthquake”, *IEEE Geoscience and Remote Sensing Letters* **10**, 372-376.

Chao, W., Wu, Y., and Zhao, L., [2010]. “An automatic scheme for baseline correction of strong-motion records in coseismic deformation determination”, *Journal of Seismology* **14**, 495-504.

Colosimo, G., Crespi, M., and Mazzoni, A., [2011]. “Real-time GPS seismology with a stand-alone receiver: A preliminary feasibility demonstration”, *Journal of Geophysical Research* **116**, B11302, 14p.

Cressie, N., [1991]. *Statistics for spatial data* (John Wiley & Sons, New York).

Graizer, V. M., [1979]. “Determination of the True Ground Displacement by Using Strong Motion Records”, Izv. USSR Acad. Sci., Physics Solid Earth 15(12), 875-885.

Graizer, V. M., [2005]. “Effects of tilt on strong motion data processing”, Soil Dyn. Earthq. Eng. 25, 197-204.

Graizer, V. M., [2006]. “Tilts in Strong Ground Motion”, Bull. Seism. Soc. Am. 96, 2090-2106.

Graizer, V. M., [2010]. “Strong Motion Recordings and Residual Displacements: What Are We Actually Recording in Strong Motion Seismology?”, Seism. Res. Letters, No.4, 635-639.

Hashimoto, M., [2013]. “Crustal deformation associated with the 2011 Tohoku-Oki earthquake: An overview”, *Earthquake Spectra* **29**, S81-S98.

Hayashi, Y., Katukura, H., Watanabe, T., Kataoka, S., Yokota, H., and Tanaka, T., [1991]. “Reliability of integrated displacement from accelerograms by digital accelerographs”, Journal of Structural and Construction Engineering, AIJ, No. 419, 57-66.

Hirai, T., and Fukuwa, N., [2012]. “Estimation of crustal deformation and magnitude of the 2011 off the Pacific coast of Tohoku earthquake using strong ground motion records”, *Proceedings of the 15th World Conference on Earthquake Engineering* Paper No.371, 10p.

Iwan, W., Moser, M., and Peng, C., [1985]. “Some observations on strong-motion earthquake measurement using a digital accelerograph”, *Bulletin of the Seismological Society of America* **75**, 1225-1246.

Katukura, H., Ohno, S., and Izumi, M., [1989]. “Symmetrical FFT technique and its applications to earthquake engineering”, Earthquake Engineering and Structural Dynamics,Vol. 18, 717-725.

Liu, Z., Owen, S., and Moore, A., [2014]. “Rapid estimate and modeling of permanent coseismic displacements for large earthquakes using high-rate global positioning system data”, *Seismological Research Letters* **85** (2), 284-294.

Lu, Y., and Panagiotou, M., [2014]. “Characterization and representation of strong near-fault ground motions using wavelet-based cumulative pulse extraction”, *Proceedings of the 10th National*

Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Paper No.348, 11p.

Niu, J., and Xu, C., [2014]. “Real-time assessment of the broadband coseismic deformation of the 2011 Tohoku-Oki earthquake using an adaptive Kalman filter”, *Seismological Research Letters* **85**(4), 836-843.

Ozawa, S., Nishimura, T., Suito, H., Kobayashi, T., Tobita, M., and Imakiire, T., [2011]. “Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake”, *Nature* **475** (7356), 373-377.

Sagiya, T., [2004]. “A decade of GEONET: 1994-2003 The continuous GPS observation in Japan and its impact on earthquake studies”, *Earth Planets Space* **56**, xxix-xli.

Wang, R., Schurr, B., Milkereit, C., Shao, Z., and Jin, M., [2011]. “An improved automatic scheme for empirical baseline correction of digital strong-motion records”, *Bulletin of the Seismological Society of America* **101**, 2029-2044.

Wang, R., Parolai, S., Ge, M., Jin, M., Walter, T., and Zschau, J., [2013]. “The 2011 Mw 9.0 Tohoku earthquake: Comparison of GPS and strong-motion data”, *Bulletin of the Seismological Society of America* **103**, 1336-1347.

Wu, Y., and Wu, C., [2007]. “Approximate recovery of coseismic deformation from Taiwan strong-motion records”, *Journal of Seismology* **11**, 159-170.

Yamagiwa, A., Hatanaka, Y., Yutsudo, T., and Miyahara, B., [2006], “Real-time capability of GEONET system and its application to crust monitoring", *Bulletin of the Geographical Survey Institute* **53**, 27-33.

Zumberge, J., Heflin, M., Jefferson, D., Watkins, M., and Webb, F., [1997]. “Precise point positioning for the efficient and robust analysis of GPS data from large networks”, *Journal of Geophysical Research* **102**, 5005-5017.