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ESTIMATION OF GEODETIC DISPLACEMENTS IN THE 2011 TOHOKU EARTHQUAKE FROM ACCELEROGRAMS AND GPS DATA

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ABSTRACT

Estimation of coseismic displacement during the 2011 Mw9.0 Tohoku-oki earthquake was estimated, by using strong motion seismographs and GNSS earth observation networks. We first evaluate the accuracy of the coseismic displacement obtained from strong motion record by comparing with the spatial distribution of the coseismic displacement from GPS, which has an accuracy level of some millimeters. Besides, a new baseline correction method for KiK-net is proposed. In this method there is no need to use some shape functions like step or ramp function to obtain final results.

Keywords: crustal movement, 2011 Tohoku earthquake, GPS data, acceleration record

INTRODUCTION

The Mw9.0 Tohoku-oki earthquake occurred on March 11, 2011, off the Pacific coast of northeastern (Tohoku) Japan, caused large crustal displacements. According to the GNSS Earth Observation Network (GEONET) at the Geospatial Information Authority (GSI), Japan, coseismic displacements (crustal movements) with maximums of 5.3 m to the horizontal (southeast) and 1.2 m to the vertical (downward) directions were observed over a wide area (Ozawa et al. 2011). Besides, the Tohoku earthquake has induced several earthquakes in the northeastern area of Japan. One of them was the Mw7.0 Fukushima earthquake, which occurred one month after in Iwaki city (36.946°N, 140.673°E according to the Japan Meteorological Agency).

The estimation of crustal displacements is of great importance because it provides information on the slip distribution and the source location and extent. Different technologies have been applied in this purpose. In the field of remote sensing, Synthetic Aperture Radar (SAR) data from TerraSAR-X satellite were used to propose an improved spatial cross-correlation (pixel-offset) method in capturing large-scale tectonic movements during the Tohoku earthquake (Liu & Yamazaki 2013). Global Navigation Satellite Systems (GNSS) data were also used by different techniques. Baseline analysis using ultra rapid ephemerides of the International Global Navigation Satellite Systems Service (IGS) were applied to GEONET stations' records to obtain static coordinates before and after the Tohoku earthquake (Ozawa et al. 2011). The RTNet GPS solutions company (http://rtgps.com) used the 1-Hz GPS data and final ephemerides, and an applied Kinematic Precise Point Positioning (KPPP) technique to obtain seismic waveforms and provided to the scientific community free of charge. A new additional processing for KPPP results was developed in order to use rapid ephemerides instead of the final ephemerides (Liu et al. 2014).

Theoretically, displacements can be calculated from acceleration records obtained by accelerometers by double integration. However, a direct application of integration produces overestimated displacements if a baseline correction is not applied. Several comparisons between

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coseismic displacements obtained from acceleration records and GPS data have been done in order to judge the accuracy of baseline correction methods (Boore 2001; Wu & Wu 2007; Wang 2013). For good comparison, the distance between GPS and seismometer stations must be close enough to consider that both had the same coseismic displacement. Boore (2001) compared 4 pairs of stations (strong motion and GPS) whose distance were less than 6.5 km. Wu & Wu (2007) used 16 pairs of stations with a distance less than 4 km. Wang et al. (2013) used 15 pairs of stations with a distance less than 3.9 km. It is observed that no big amount of data were available in order to compare the performance of baseline correction methods.

In this study, the spatial distribution of coseismic displacements is estimated from displacements recorded at GEONET stations during the 2011 Tohoku earthquake. Then, the acceleration records from all the seismic stations in the study area can be used for comparing with those from GPS records. Such a large amount of data pairs will be useful in a better comparison of the baseline correction methods.

BASELINE CORRECTION OF STRONG MOTION RECORDS

Since strong motion accelerometer networks are deployed around the world, several efforts have been carried out to obtain displacements from acceleration records. As mentioned previously, numerical integration procedures can be applied to calculate displacement waveforms, by a linear acceleration method as follows:

$$\dot{x}_{i+1} = \dot{x}_i + \frac{\Delta t}{2}\left(\ddot{x}_i + \ddot{x}_{i+1}\right) \tag{1a}$$

$$x_{i+1} = x_i + \dot{x}_i \Delta t + \frac{\Delta t^2}{6}\left(2\ddot{x}_i + \ddot{x}_{i+1}\right) \tag{1b}$$

where x_i, $\dot{x}_i$, $\ddot{x}_i$ denote the displacement, velocity, acceleration at a time instant i, respectively, and Δt is the time interval. In most cases, the application of Eq. (1) produces an overestimated displacement (Figure 1c). The main reason of this effect is due to a slight shift of the baseline in the acceleration record, whose amplitude varies with time. Although this baseline shift cannot be appreciated in the acceleration record, it affects the velocity and displacement waveforms (Figure 1b and 1c). The mentioned baseline shift varies in time and is quite difficult to determinate its real trend. However, most researchers estimated it as a constant value during a strong shaking of an acceleration record and another value for a latter shaking part (Iwan et al. 1985; Boore 2001; Wu & Wu 2007; Chao et al. 2010; Wang et al. 2011)

The effect of baseline shift is easily observed in the velocity record, which has a linear trend for most cases (Figure 1d). Besides, the slope of this linear trend represents the baseline shift in the acceleration record. The linear trend observed during the strong shaking part and latter part can be expressed as:

$$v_m(t) = v_{m0} + a_m t\,;\ t_1 \le t < t_2 \tag{2a}$$

$$v_f(t) = v_{f0} + a_f t\,;\ t_2 \le t \tag{2b}$$

$$v_m(t_2) = v_f(t_2) \tag{2c}$$

where, a_m denotes the baseline shift between times t_1 and t_2, and a_f the baseline shift from t_2 to the end of the record. When the lines v_m and v_f are removed from the velocity record, the processed velocity is denominated as the corrected velocity record. Then, corrected displacement can be calculated. Note that there is no procedure that can recover the real strong-motion from an acceleration record and the adjective “corrected” used in this paper implies only that the linear trend has been removed. The linear trend in the latter part v_f can easily be found by a least-square fitting method, however, v_m depends on

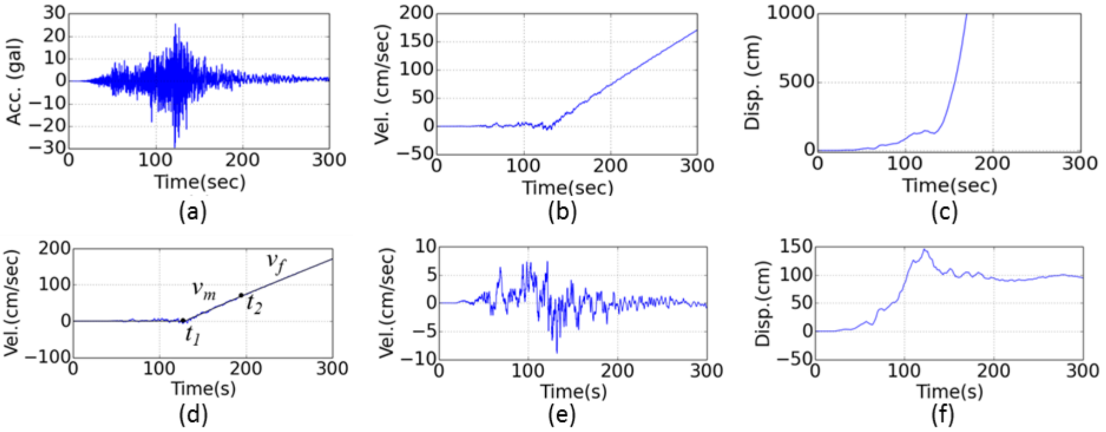


Figure 1. Baseline correction. (a) acceleration record; (b) uncorrected velocity; (c) uncorrected displacement; (d) linear trend ; (e) corrected velocity; (f) corrected displacement.

the time parameters t_1 and t_2, which are not directly calculated. Several approaches have been proposed to estimate t_1 and t_2 (Iwan et al. 1985; Wu & Wu 2007; Wang et al. 2011).

Iwan et al. (1985) propose two different approaches to estimate t_1 and t_2. In the first approach, the times of first and last occurrences of acceleration a(t) > 50 cm/s^2 should be selected as t_1 and t_2. In the second approach, t_1 is selected as the first significant acceleration pulse and then select t_2 in a way that the final displacement is minimized. Boore (2001) showed that in some cases the final displacement is sensitive to the selection of t_2. Wu & Wu (2007) pointed out that the corrected displacement record shows a flat shape in the latter shaking part, therefore they estimated t_1 as the time when the displacement moves from the zero line and t_2 should be chosen iteratively in a way that the corrected displacement record best fits to a ramp function. Wang et al. (2013) proposed a procedure in which t_1 and t_2 are estimated in an iterative procedure in a sense that the corrected displacement record best fits a step function. More detailed information of these methods can be found in the references.

COSEISMIC DISPLACEMENT DISTRIBUTION IN THE TOHOKU EARTHQUAKE

Strong Motion Seismograph and GPS networks in Japan

Dense strong motion networks have been established in Japan after the 1995 Hyogoken-Nanbu (Kobe) earthquake by the National Research Institute for Earth Science and Disaster Prevention (NIED). The Kyoshin Network (K-NET) stations are located in public offices, schools and parks. The Kiban Kyoshin network (KiK-net) stations are located in quiet places. Each KiK-net station has a borehole of around 100 m (bedrock) and strong motion accelerometers were installed at the surface and the bottom of the borehole (downhole). The total number of stations from these two networks is about 1,700.

On the other hand, the Geospatial Information Authority of Japan (GSI) operates the GNSS Earth Observation Network System (GEONET), having over 1,200 stations with about 20 km interval, and the system monitors the movement of Japanese land territory.

Coseismic displacement distribution from Kriging interpolation method

The result of spatial distribution of the coseismic displacement is presented in this section. The GEONET stations used in this study are shown in Figure 2a by blue dots. The study area contains the stations where large displacements were observed. The recorded displacements at these stations were interpolated by Eq. (3) to estimate the coseismic displacement distribution:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{3}$$

where $Z(s_i)$ denotes the measured value at location s_i (an observed displacement by GEONET), $\hat{Z}(s_0)$ the predicted displacement, λ_i an unknown weight for the measured value $Z(s_i)$, s_0 the location of a predicted value, and N is the number of measured values. The weight factors (λ_i) depend on the distance between the measured points (s_i) and the prediction location (s_0). The weight factors also depend on the spatial arrangement of the measured points, which is quantified by the spatial autocorrelation. A spherical model was used to fit semivariograms and to estimate the spatial autocorrelation. The nearest fifteen GEONET stations were used to calculate a predicted displacement $\hat{Z}(s_0)$.

The displacements at GEONET sites were calculated from the difference of its coordinates between the days 10 and 12 March 2011, which were provided by GSI. Figure 2b and 2c show the coseismic displacement distribution from Kriging method. The black arrows indicate the GPS displacemenst and the colour shading indicates the displacement distribution from Kriging method. Red colour shows the area with large displacements. Rather uniform variation of displacements is observed in the horizontal component (Figure 2b); however, the vertical displacement (subsidence) is large near the coastline (Figure 2c). In order to evaluate the reliability of our results, GEONET stations 0546 and 0937 were removed from the input data values and Kriging method was applied again. The differences between the real value at the GEONET stations (0546 and 0937) and those obtained by the interpolation were less than 2%.

Coseismic displacement distribution from acceleration records

After coseismic displacement distribution from Kriging method became available in the whole study area, it was compared with the displacements obtained from acceleration records. In the study area, 310 K-NET stations and 198 KiK-net stations recorded the mainshock of the Tohoku earthquake. Considering that KiK-net stations have two accelerometers (bedrock and surface) and each provides three components (east-west, north-south, and up-down), a total of 2,118 records are available. In this study, several approaches were adopted to remove the baseline shift from the acceleration records and to obtain displacement time histories (Iwan et al. 1985; Chao et al. 2010; Wang et al. 2011). The results from the method proposed by Wang et al. (2011) showed the best performance and agreed well with the results from Kriging method. Only the results from Wang’s method is presented in this paper.

In Figure 3, the EW component of coseismic displacements obtained from Kriging of the GEONET

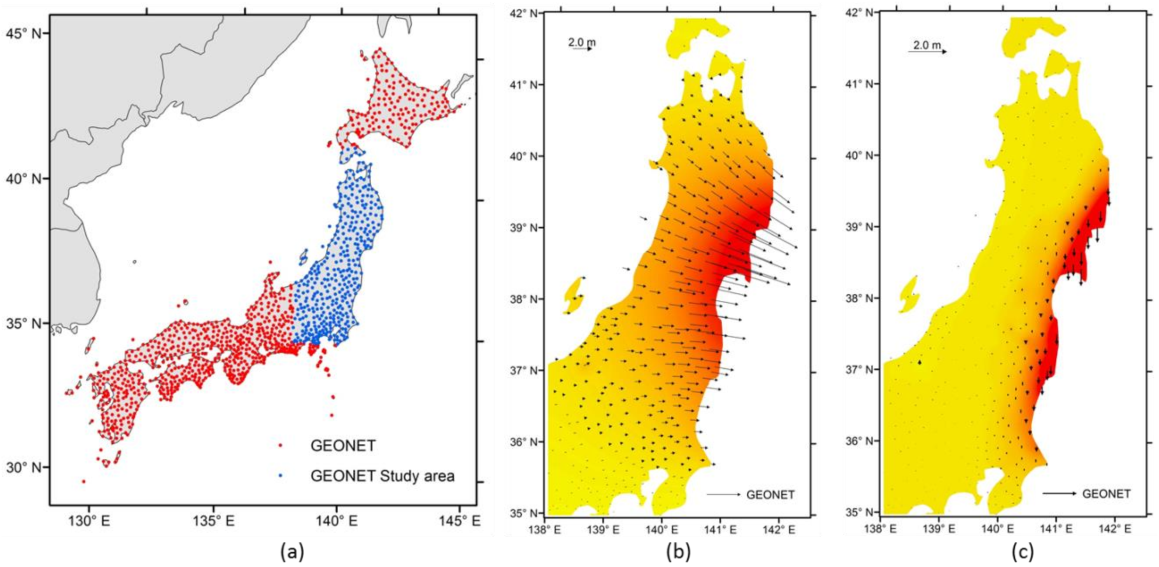
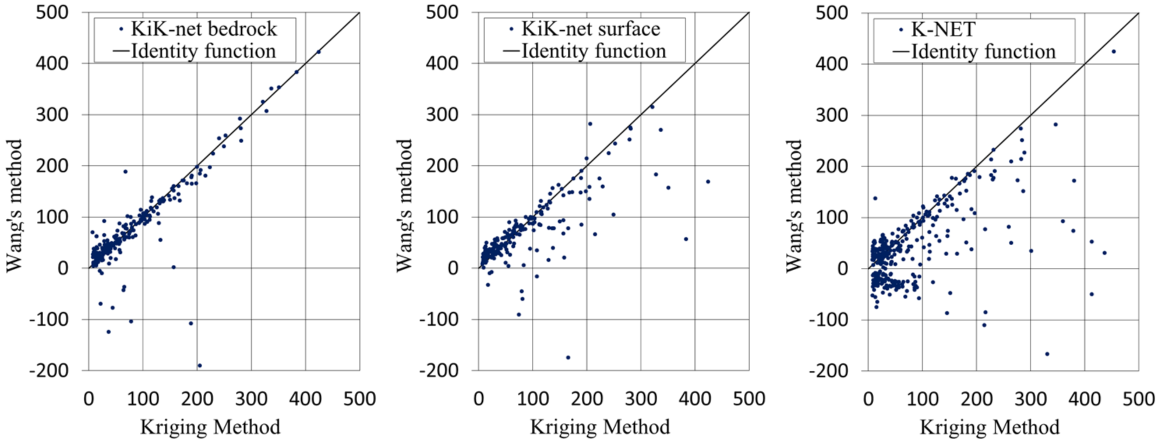


Figure 2. The study area and displacement distribution by Kriging. (a) Blue dots represent the GEONET stations used in this study; (b) horizontal displacement distribution; (c) vertical displacement distribution.



(a) KiK-net bedrock (b) KiK-net surface (c) K-NET surface

Figure 3. Comparison of coseismic displacements to the east-west (EW) direction obtained from Kriging of GEONET data and from acceleration records.

data and from the acceleration records are compared. The results from the accelerations recorded at bedrock agree quite well with those from Kriging method. On the contrary, it is noticed that several surface records show big difference compared with those by Kriging method. Several reasons might be attributed to some differences. The accelerometers located on the surface were affected by the site response characteristics. It has been mentioned by Wang et al. (2013) that the majority of K-NET stations are located in public offices, schools, parks and free-surface of softer sediments, which could produce large tilting of accelerometers. Besides, some acceleration records might present a baseline shift with a nonlinear trend, which is impossible to remove by the approach of Wang et al. (2011). The NS components showed similar pattern with the EW components, which means better results were observed for KiK-net bedrock records. Overestimated values were obtained from some acceleration records to the vertical direction. The spatial distribution of coseismic displacements at KiK-net and K-NET stations is presented in Figure 4. The black and red arrows represent the displacements obtained from Kriging of the GEONET data and from the integration of acceleration records, respectively. As mentioned previously, small variation is observed for the KiK-net bedrock records and larger variation is observed at K-NET and some surface KiK-net sites.

BASELINE CORRECTION FOR KIK-NET STATIONS

In this paper, we presented a new use of KiK-net stations to estimate coseismic displacement distribution. As mentioned previously, in order to remove the linear trend observed in a velocity time history correctly, a good criterion to choose the time parameters t_1 and t_2 must be determined. Previous researches on this issue determine the time parameters in a way that the corrected displacement history best fits some shapes like a ramp function (Wu an Wu 2007) or a step function (Wang et al. 2011). In order to assure reasonable results, the parameters t_1 and t_2 are restricted in a certain interval under criteria proposed by different authors (Iwan et al. 1985; Wu and Wu 2007; Chao et al 2010; Wang et al. 2011).

The fact that KiK-net stations have two accelerometers (at borehole and surface) can be used to estimate the coseismic displacement without necessity of restraining the time parameter (t_1 and t_2) or fitting the result to a shape function. Considering that a residual soil deformation at the surface is much smaller than that from a geodetic displacement, the permanent displacement after an earthquake should be almost the same level at the surface and bedrock.

Since baseline shifts are produced by several factors, each accelerometer is affected by those in a different manner. Figure 5 shows the acceleration records from KiK-net station MYGH03 at the surface and bedrock (borehole). After applying numerical integration, the linear trend observed at the surface was different from the bedrock one and as a consequence, the uncorrected displacements were

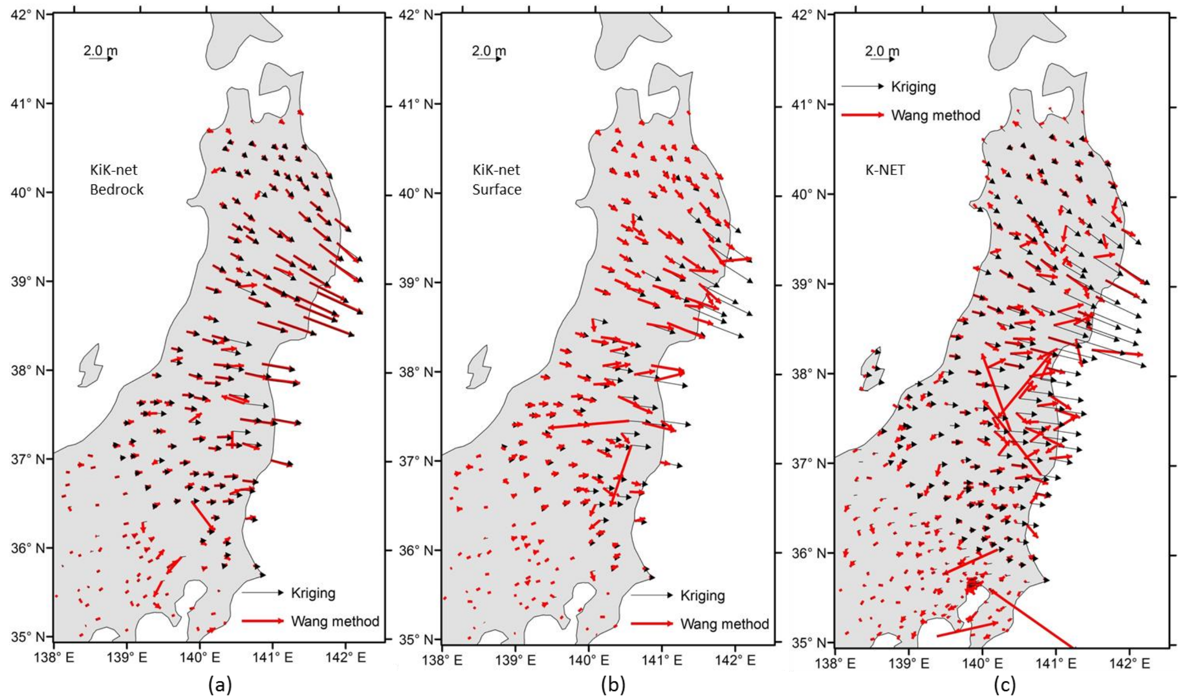


Figure 4. Permanent displacement distribution after the Tohoku earthquake obtained from Kriging of GEONET data (black arrows) and from the integration of acceleration records (red arrows). Lateral displacements at KiK-net bedrock (a), KiK-net surface (b) and K-NET surface (c) sites.

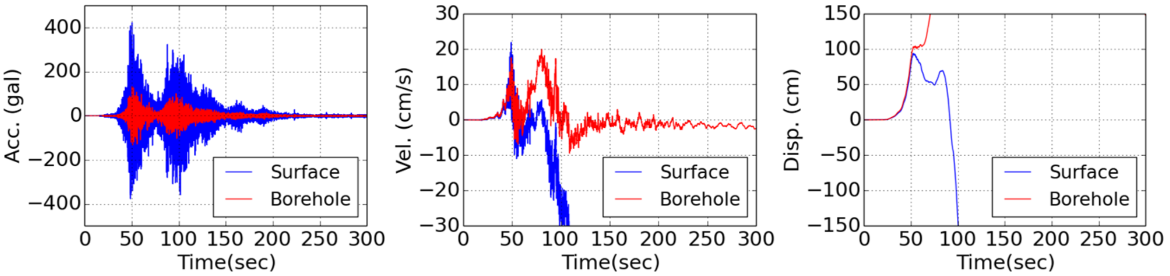
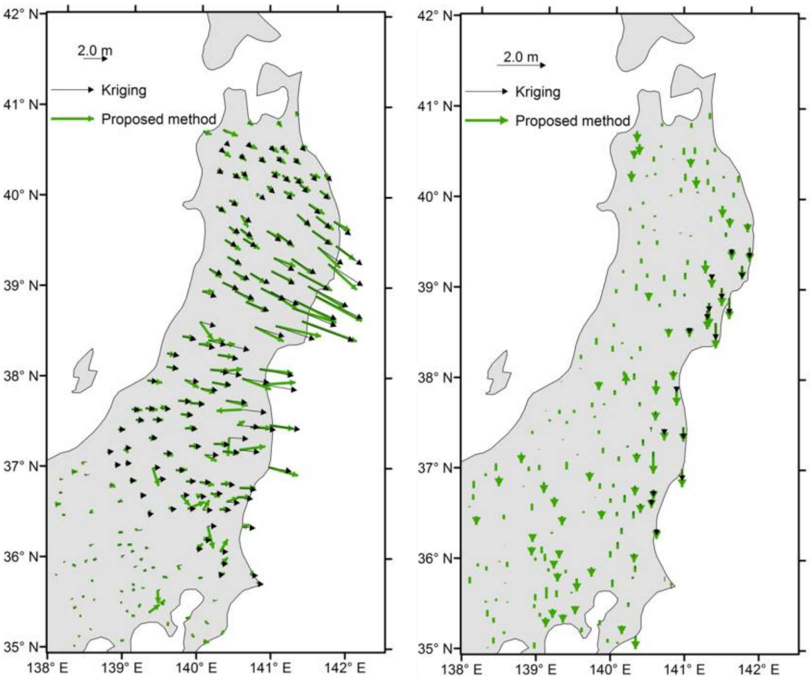


Figure 5. Acceleration (left), uncorrected velocity (center) and uncorrected displacement (right) from KiK-net station MYGH03 during Tohoku-oki earthquake.

different. Therefore, only the corrected displacement obtained from the both records will produce a unique result. In order to evaluate the similarity of the corrected displacements at borehole and surface, we introduce a parameter called *pseudo-variance*, *S*, such as

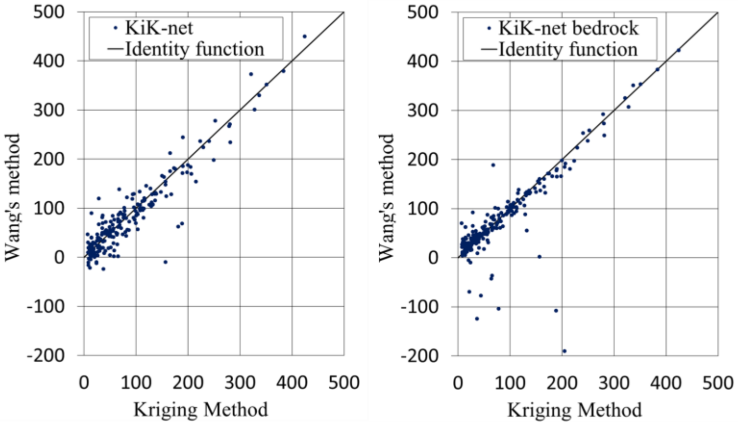
$$S\left(t_1^b,t_2^b,t_1^s,t_2^s\right)=\sum_{j=1}^{N}\left(D^b\left(t_1^b,t_2^b\right)_j-D^s\left(t_1^s,t_2^s\right)_j\right)^2 \qquad (4)$$

Where, D^b and D^s are the corrected displacements from the records at the borehole and surface, respectively. The time parameters t_1^b,t_2^b belong to the strong motion recorded at the borehole and t_1^s,t_2^s belong to that at the surface. The sub index *j* denotes a position of a control point in the records and *N* denotes the number of control points. If the number of control points is equal to the number of data, the pseudo-variance will be equal to *N* times of the *variance*. The objective of our proposal is to find the combination of time parameters (t_1^b,t_2^b,t_1^s,t_2^s) that will produce the minimum value of the pseudo-variance. There are many options to find the minimum value of *S*; it can be obtained by a suitable windowing or by some optimization techniques. It is first necessary to express the corrected displacement of a control point as a function of the time parameters. This issue is solved in a



(b) Horizontal component (b) Vertical component

Figure 8. Coseismic displacements from Kriging of GEONET data and from the integration of acceleration records using the proposed joint parameter determination at KiK-net sites.



(b) The proposed joint search (b) Wang's method

Figure 9. Comparison of coseismic displacements to the EW direction obtained from Kriging of GEONET data and from the integration of acceleration records.

straightforward manner from its mathematical meaning. Here, the corrected displacement at some instant represents the difference between the uncorrected displacement and the integration of a linear trend observed in the velocity history. Therefore, for a control point *j*, the corrected displacement is expressed as:

$$D_j = \begin{cases} d_j - \int_{t_1}^{t_j} (a_m t + v_{0m}) dt & ; t_1 \le t_j < t_2 \\ d_j - \int_{t_1}^{t_2} (a_m t + v_{0m}) dt - \int_{t_2}^{t_j} \left(a_f t + v_{0f}\right) dt & ; t_2 \le t_j \end{cases} \tag{5}$$

where, d_j denotes the uncorrected displacement and t_j represents the time at which the control point is located. Figure 6 shows the coseismic displacement distribution after the Tohoku earthquake estimated from our proposal. We use fifty control points and an iterative windowing to find the time parameters. The results show a better spatial variability than the results obtained only from KiK-net surface data. It demonstrates that there exist better time parameters t_1 and t_2 for KiK-net surface accelerometers than the ones obtained from the previous methods. On the other hand, the results obtained only from KiK-net borehole accelerometers (Figure 4) presents better results at some stations and poorer in others, as can be observed in Figure 7.

CONCLUSIONS

The accuracy of coseismic displacements obtained from strong motion data after apply a suitable baseline correction method was evaluated. The displacement data recorded at GEONET sites were employed first to obtain the spatial distribution of coseismic displacements by Kriging and the results were compared with the displacements obtained from double integration of acceleration records. Reliable results were found only for the acceleration records at bedrock. A high level of variability was observed for the coseismic displacements evaluated from the acceleration records at the surface. Besides, a method to estimate coseismic displacements by a joint parameter search at each KiK-net site was developed. Using this method, an improvement in the baseline correction for the surface records was achieved but it was not so successful for the records at the borehole. For the case of strong motion records at the surface, we demonstrated that there exist a better method to determine time parameters than the one obtained from the current methods. Quite reasonable results were obtained from our proposed method because the Tohoku-oki earthquake produced geodetic displacements with the order of some meters and thus surface soil deformation was considerably lower than those at most of the stations. Therefore, it is necessary to test the performance of the method with other events in the future.

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