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COMPARISON OF COSEISMIC DISPLACEMENTS OBTAINED FROM STRONG MOTION ACCELEROGRAMS AND GPS DATA IN JAPAN

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ABSTRACT

Strong motion seismometers and GNSS (Global Navigation Satellite System) earth observation networks cover uniformly the region of Japan. Since the availability of such amount of information is rare in other countries, good opportunity to compare coseismic displacements from acceleration records and GPS data is provided. Two events were chosen in this study: the 11 March 2011 M_W9.0 Tohoku earthquake and the 11 April 2011 M_W6.6 Fukushima-Hamadori earthquake, which was an induced event by the previous one. Since the baseline in an acceleration record showed a shift and it changed in time during an event, this study investigated several baseline correction methods proposed in other studies. Strong-motion and GPS stations were selected from the two events and coseismic displacements evaluated from GPS data and acceleration records were compared.

INTRODUCTION

The Mw9.0 Tohoku earthquake occurred on March 11, 2011 off the Pacific coast of northeast (Tohoku) Japan, caused gigantic tsunamis, resulting in widespread devastation. According to the GNSS Earth Observation network (GEONET), operated by the Geospatial Information Authority of Japan (GSI), 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 of the mainland (Ozawa et al. 2011).

The Tohoku earthquake has induced several earthquakes in the eastern part of Japan. One of them was the M_W 6.6 (M_{JMA} 7.0) Fukushima (-Hamadori) earthquake, which occurred one month after the Mw9.0 event, in Iwaki city around 230 km southwest of the epicentre of the Tohoku earthquake. The epicentre of the Fukushima earthquake was 36.946^{O}N and 140.673^{O}E with depth 6.4 km (Japan Meteorological Agency 2011). The coseismic slip associated with the Fukushima event was generated by a known active fault zone. Large displacements were observed along the Itozawa and Yunodake faults, while smaller offsets were observed along other faults (Lin et al. 2013; Toda and Tsutsumi 2013).

Several researches have been carried out to estimate coseismic and postseismic displacements from satellite Synthetic Aperture Radar (SAR) data. Kobayashi et al. (2012) applied Interferometric SAR (InSAR) analysis using ALOS/PALSAR data in the Fukushima-Hamadori area and mapped the ground displacement produced by the Fukushima event. Liu and Yamazaki (2013a, 2013b) recently introduced high-accuracy georeferenced SAR data observed from TerraSAR-X satellite for the Tohoku and Fukushima earthquakes and they proposed an improved spatial cross-correlation (pixel-

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offset) method to capture tectonic movements from the location of intact buildings. Although the use of satellite images is useful to estimate geodetic displacements in a wide area (high spatial-resolution), those methods are limited by the time-interval of satellite image acquisitions (low temporal-resolution) and thus cannot be used for capturing displacement time histories.

Since strong motion seismometer networks are now deployed around the world, a reliable procedure to obtain coseismic displacements from acceleration records should be established as an alternative of GPS stations. Dense strong-motion networks have been deployed after the 1995 Kobe earthquake throughout Japan, namely K-NET with 1,000 stations and KiK-net with 700 stations. Each KiK-net station has surface and borehole (bedrock) accelerometers while a K-NET station has only a surface accelerometer. Besides, the GEONET system has 1,200 GNSS-based ground control stations throughout the country. Real-time observation of coseismic displacements was made possible by continuous observation at the GEONET stations, where radio waves from the GPS satellites are constantly received. Thus, the movement of the land of Japan is daily monitored by GEONET. Since some seismometer stations are located close enough to a GPS station, comparison of coseismic displacements calculated from these different sources of data is possible (Hirai and Fukuwa 2012; Wang et al. 2013).

In this paper, coseismic displacements in the Fukushima prefecture during the M_W 9.0 11 March 2011 Tohoku earthquake and the M_W 6.6 11 April 2011 Fukushima earthquake are calculated from GPS data and acceleration records. The seismometer stations located close to GPS stations are used for the comparison of coseismic displacements.

BASELINE CORRECTION OF STRONG–MOTION RECORDS

In most cases, direct double integration of an acceleration record produces a diverged displacement as shown in Figure 1. This anomaly was produced by a slight shift of the baseline in the acceleration record, whose amplitude varies with time. Although the baseline shift is not so clear in the acceleration record, it affects the displacement, obtained by double integration.

Due to the variation in time of the baseline shit, it seems very difficult to reveal its real behaviour. However, most researchers estimate it as a constant value during the strong shaking part of an acceleration record and another value in the latter part (Iwan et al. 1985; Boore 2001; Wu and Wu 2007; Wang et al. 2011).

The effect of the baseline shift is easily observed in the velocity record shown in Figure 1b, which has a linear trend after a certain starting time. Note that the slope of the linear trend in a velocity record corresponds to the baseline shift in an acceleration record. Following the same terminology as the previous studies, the linear trend can be expressed as:

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

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

$$v_m(t_2) = v_f(t_2) \tag{3}$$

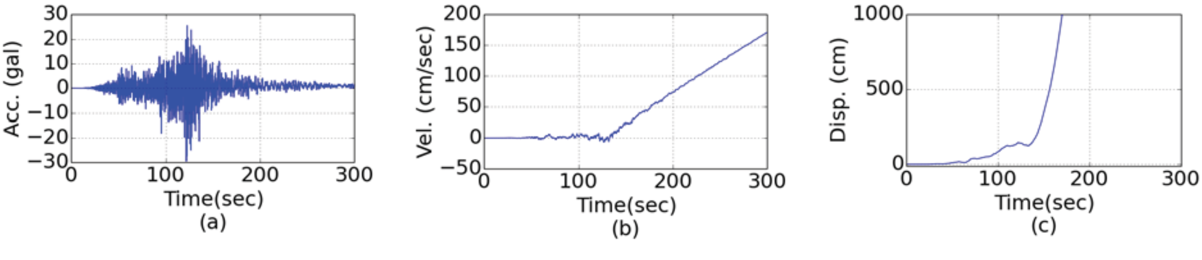


Figure 1. Direct double integration without baseline correction for a KiK-net FKSH04 station record (2011/3/11) in the EW direction; acceleration (a), velocity (b) and displacement (c)

where a_m denotes the baseline shift between times t_1 and t_2, and a_f the baseline shift from time t_2 to the end of the record. When the lines v_m and v_f are removed from the velocity record, it is denominated as the corrected velocity record. Then, the corrected displacement record can be calculated by a direct integration in the time domain. Since the line v_f can easily be found by least-squares fitting, the main issue is to find the time parameters t_1 and t_2 and several approaches have been proposed for this step.

Iwan et al. (1985) proposed two different approaches to estimate t_1 and t_2. In the first approach, the times of the 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 a final displacement is minimized. Boore (2001) showed that in some cases the final displacement is sensitive to the selection of t_2. Wu and Wu (2007) pointed out that the corrected displacement record shows a flat shape in the latter time interval, and thus they estimated t_1 as the time when the displacement move 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 should be estimate in an iterative procedure in a sense that the corrected displacement record best fits to a step function. Please refer to the original references for more details of the baseline correction methods of acceleration records.

PRECISE POINT POSITIONING OF GPS DATA

The precise point positioning (PPP) technique of GPS data can estimate the position of a single point without the requirement of a reference station or baseline (Zumberge et al. 1997); it represents a great advantage since during an earthquake the reference station is also in motion. However, to accomplish this technique a precise ephemerides and highly accurate clocks are needed. The International GNSS Service (IGS) provides such information but it takes some days after the last acquisition of a record. In this study, seismic ground motion is analysed using 1-Hz sampling GPS data provided by the Geospatial Information Authority of Japan (GSI).

In this study, the GPS's PPP technique is performed by two ways; one using RTKLIB (http://www.rtklib.com/), an open-source program package for GNSS positioning, and another a web service MagicGNSS (http://magicgnss.gmv.com), provided by GMV company. The magicGNSS web service is aimed to people who are not familiar with GNSS, and it processes the GPS data automatically as a black box and provides a report with the configuration used and the quality of the results.

The RTNet software (http://rtgps.com) of GPS Solutions, Inc. also processed the most of the GEONET station’s data in the mainshock of the 2011 Tohoku earthquake and the processed 1-Hz sampling data are made available to the scientific community.

Figure 2 shows an example of the processed results using the RTKLIB software and magicGNSS web-service for the GEONET Kesennuma (0172) station (30.9039^{O}N, 141.5726^{O}E). The results by the RTNet software were also plotted for comparison. The displacement time histories calculated from RTKLIB and magicGNSS agree well with RTNet results in the east-west (EW) and north-south (NS) directions. In the up-down (UD) direction, the displacement obtained from the RTKLIB software shows slight differences from the two other results, but the overall agreement of the three results look very good. Hence in this paper, we will use the RTKLIB software hereafter.

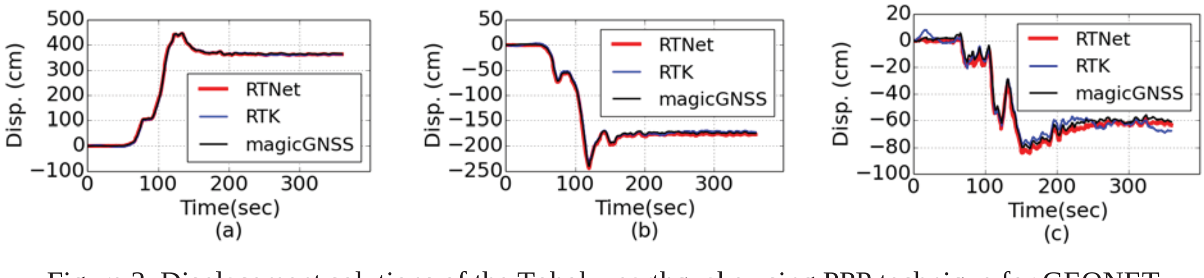


Figure 2. Displacement solutions of the Tohoku earthquake using PPP technique for GEONET Kesennuma (0172) station during the 2011 Tohoku event; EW (a), NS (b) and UD (c) components

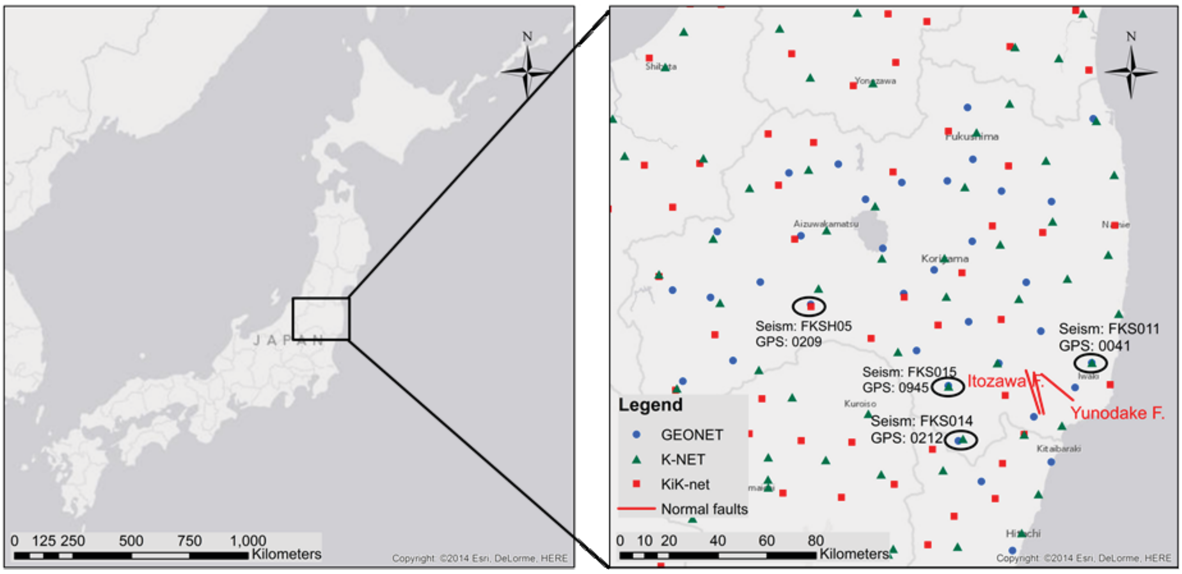


Figure 3. Location of GEONET, KiK-net and K-NET stations that were selected to compare coseismic displacements obtained from GPS data and acceleration records

STUDY AREA, DATA USED, AND THE METHOD OF ANALYSIS

The study area was focused on the Fukushima prefecture and its vicinity, Japan. Figure 3 shows the location of GEONET, KiK-net, and K-NET stations in the study area. Four pairs of GPS and seismometer stations were chosen to compare coseismic displacements. One of the seismometer stations (FKSH05) is from KiK-net (both downhole and surface) and three (FKS011, FKS014, and FKS015) from K-NET (surface). The downhole accelerometer at FKSH05 is located at a depth of 105m.

Acceleration records from KiK-net and K-NET stations during the Tohoku (2011/03/11) and Fukushima (2011/04/11) earthquakes were provided by National Research Institute for Earth Science and Disaster Prevention (2011) and 1-Hz sampling GPS data from GEONET stations were provided by Geospatial Information Authority of Japan (2011).

The baseline correction method proposed by Wang et al. (2013) was used in this study since it is more general than the others and have an advantage that its procedure is automatic and hence no user interference is required. Due to the complexity of the procedure, it is not presented here but well documented in its original publication.

A PPP technique of kinematic mode in the RTKLIB software was used for ionosphere correction with ionosphere-free linear combination (LC) of the dual-frequency carrier-phase GPS observables. The precise troposphere model was applied considering the tropospheric zenith total delay, tropospheric zenith hydro-static delay, hydro-static mapping function and wet mapping function. The earth-centered earth-fixed (ECEF) coordinate system was used in the analysis. Solid earth tides, ocean tide loading, and pole tides were considered in the estimation of site displacements by earth-tides. Precise ephemerides, 30-s satellite clocks, and absolute antenna PCV (phase center variation) models were provided by IGS. The precise satellite position at every 15 min was used with an appropriate interpolation performed by the software. More detail of the models and configurations can be found on the software's manual (http://www.rtklib.com/).

RESULTS FOR THE 2011 TOHOKU EARTHQUAKE

Coseismic displacements due to the 2011 Tohoku earthquake were calculated from the GPS stations in the Fukushima prefecture using the kinematic PPP technique and the results are shown in Figure 4. The displacement distribution agrees well with the previous publications (Ozawa et al. 2011; Hashimoto 2013). The horizontal displacements are directed almost eastward with larger amplitudes in

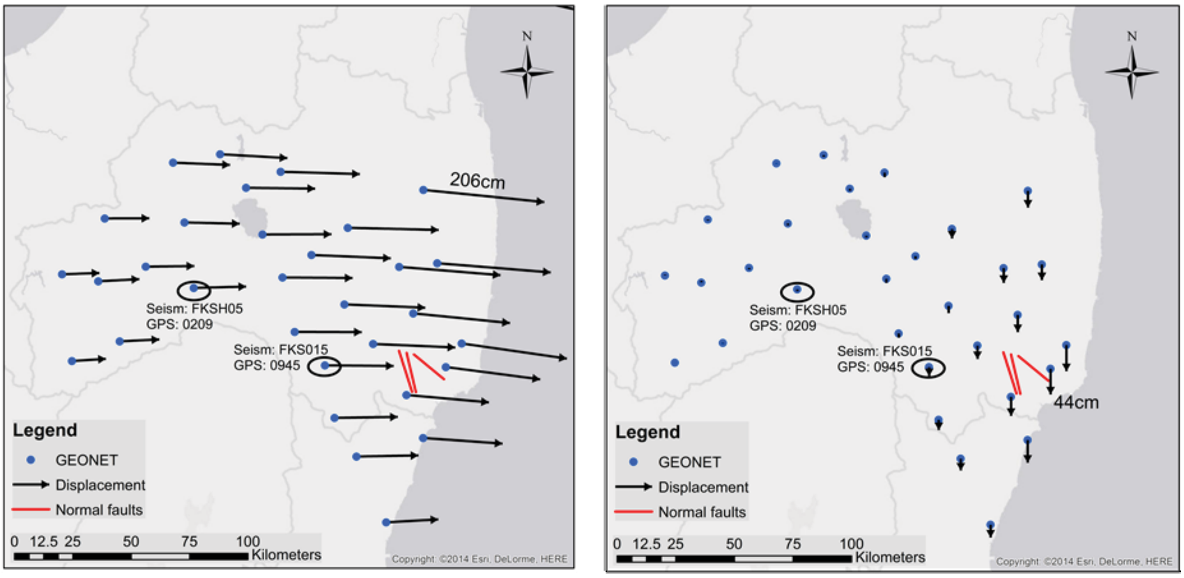
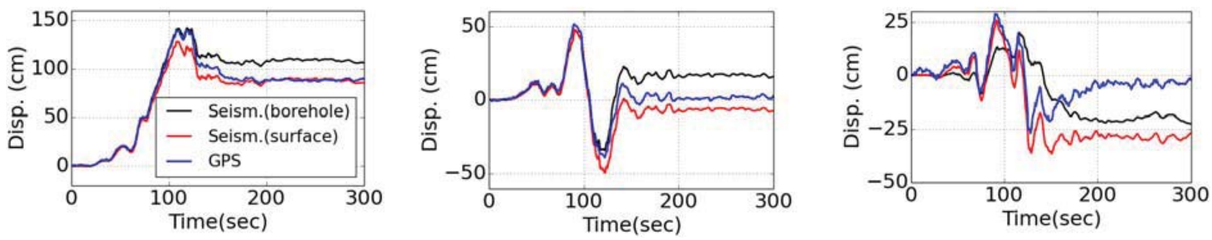
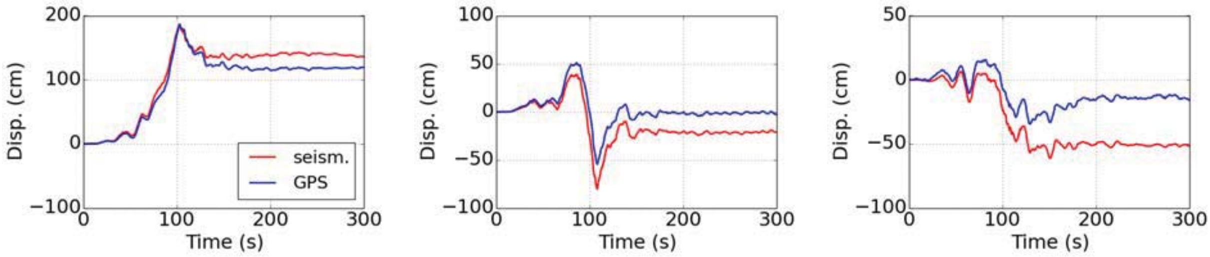


Figure 4. Coseismic displacement distribution due to the 11 March 2011 Tohoku earthquake to the horizontal (left) and vertical (right) directions calculated from GEONET data



(a) KiK-net station FKSH05 vs. GEONET station 0209 (distance of 0.94 km)



(b) K-NET station FKS015 vs. GEONET station 0945 (distance of 0.30 km)

Figure 5. Comparison of coseismic displacements from GPS and acceleration records during the 2011 Tohoku earthquake at the stations in Figure 4 to the EW (left), NS (middle), and UD (right) directions

the coastal area. On the contrary, vertical displacements (subsidence) are observed only in the coastal area. Since long-term subsidence had been observed before the 2011 Tohoku earthquake, uplift was expected for such a large-magnitude event (Hashimoto 2013). However, uplifts were observed near the Pacific coastal area in the post-seismic stage (Ozawa et al. 2011).

Figure 5 shows examples of corrected displacement records for KiK-net FKSH05 station and K-NET FKS015 station. The displacement records obtained from the closest GEONET stations are also plotted. The results in the EW and NS directions agree rather well between the two kinds of records. At FKSH05 site, the surface seismometer gave a better double integrated result than the downhole one. However this is not a usual case, as already demonstrated by other researchers (Hirai and Fukuwa 2012; Wang et al. 2013). We have also compared several pairs of GEONET and KiK-net datasets, and for most cases, downhole seismometers gave better results than the surface ones. This is probably due to the fact that downhole seismometers are more confined by the surrounding soils than the surface ones, and thus show closer geodetic displacements with GPS sensors.

In the vertical components, larger discrepancy was observed between the results from seismometers and GPS. Since the baseline correction method proposed by Wang et al. (2013) searches the corrected displacement that best fits to a step function, a flat shape is usually observed in the final interval of a corrected displacement. However, in the vertical displacements from the GPS data, the latter parts do not look to have a flat shape. That is why the corrected displacements from acceleration records do not agree with the GPS displacements for the vertical direction.

RESULTS FOR THE 2011 FUKUSHIMA EARTHQUAKE

Similar displacement calculations from GEONET data and acceleration records were also conducted in the Fukushima prefecture for the 11 April 2011 Fukushima earthquake. From the GPS data, significant coseismic displacements were observed only in the areas near normal fault systems named Yunodake and Itozawa, as shown in Figure 6. Normal faults locations were taken from the InSAR image of GSI (http://www.gsi.go.jp/cais/topic110425-index.html).

GEONET stations 0800 and 0946 are located on the foot wall of the Yunodake fault and on the hanging wall of the Itozawa fault, respectively. The horizontal displacement at the station 0800 looks almost perpendicular to the strike vector of the Yunodake fault; on the other hand, the horizontal displacement at the station 0946 looks parallel to the strike vector of the Itozawa fault. A large vertical displacement was observed only at the station 0946 (47 cm), while other GPS stations observed displacements less than 5 cm. Following a general behaviour of normal faults, uplift was observed at the station 0800 and subsidence at the station 0946.

Figure 7 shows examples of the comparison between the corrected displacements from accelerograms and those from 1-Hz sampling GPS data. Agreement between the both results is good when the displacement is in the order of 5 cm or larger. But for smaller displacement values, agreement is not so good because the accuracy level of the PPP technique is in the same level with the displacements here. It is also noticed that after applying the baseline correction, long-period harmonic movements were observed in the latter part of the double-integrated displacements when the values are small.

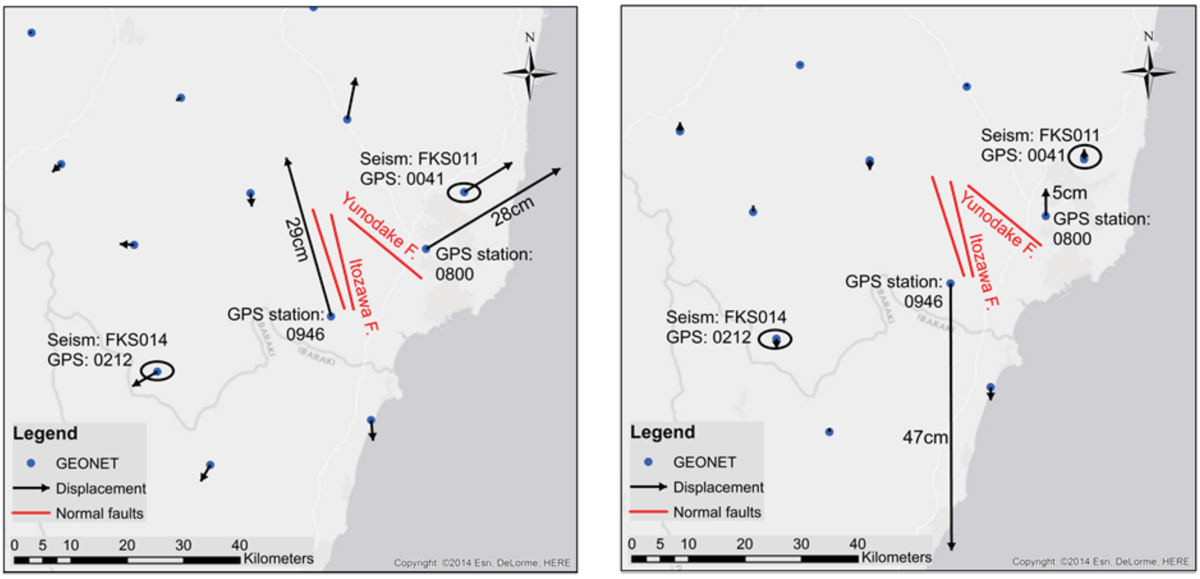
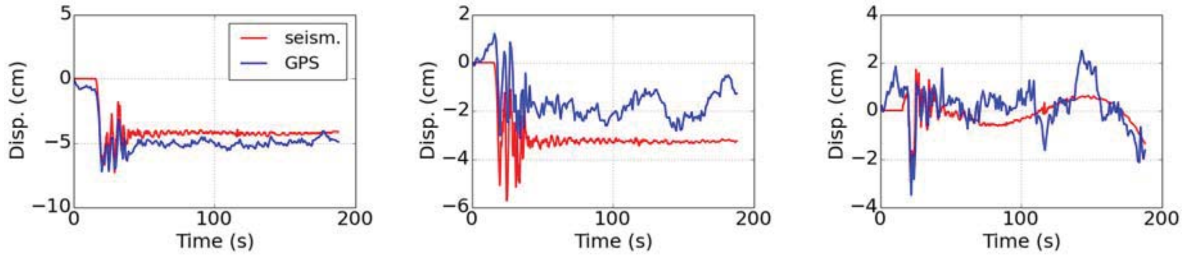
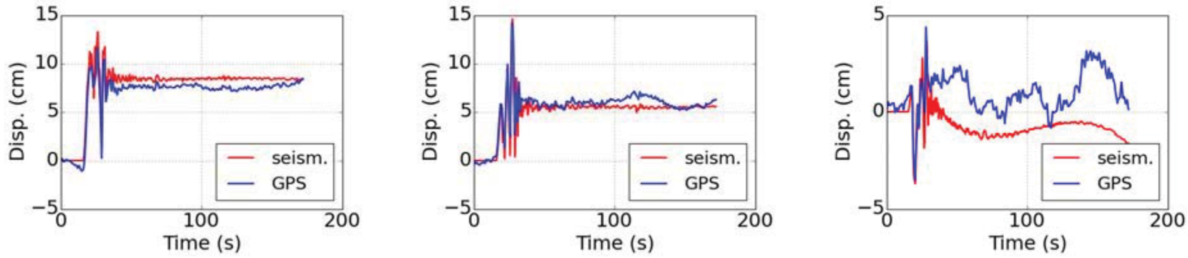


Figure 6. Coseismic displacement distribution due to the 11 Apri 2011 Fukushima earthquake to the horizontal (left) and vertical (right) directions calculated from GEONET data.



(a) K-NET station FKS014 vs. GEONET station 0212 (distance of 2.05 km)



(b) K-NET station FKS011 vs. GEONET station 0041 (distance of 0.12 km)

Figure 7. Comparison of coseismic displacements from GPS and acceleration records in the 2011 Fukushima event at the stations in Figure 6 to the EW (left), NS (middle), and UD (right) directions

CONCLUSIONS

Coseismic displacements during the M_W 9.0 Tohoku earthquake on 11 March 2011 and the M_W 6.7 Fukushima earthquake on 11 April 2011 were calculated using two different sources of data: GPS (GEONET) and seismograph networks (KiK-net and K-NET). A kinematic precise point positioning (PPP) technique was applied for the GPS data (GEONET) and time-domain double-integration with baseline correction was applied for acceleration records (KiK-net and K-NET). Then, the results from these techniques were compapred.

The displacement time histories obtained from the GPS data and acceleration records agreed well for the Tohoku earthquake. Since the PPP technique guarantees the accuracy level of some centimeters and the crustal displacements with a few meters were observed during the Tohoku earthquake, the GEONET data were considered as the truth data. In that sense, the baseline correction procedure proposed by Wang et al. (2013) generated results similar to the GPS records while some differences were still observed when the baseline correction was applied to vertical acceleration records. Comparison of displacements developed during the Fukushima earthquake has limitation because the accuracy level of the PPP technique is in the same level as the displacement records observed in the Fukushima earthquake.

Based on this study, the double integration of acceleration records was demonstrated to show a high level of accuracy when a proper baseline correction is employed. Since a number of accelerometers have been deployed in various parts of the world, the direct integration of accelerograms may be conveniently used to estimate coseismic displacements, especially for the areas without many GNSS ground control stations.

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