Generation and propagation of static displacement estimated using KiK-net recordings

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Using KiK-net strong-motion data recorded at eleven stations during the 2011 off the Pacific coast of Tohoku Earthquake (the 2011 Tohoku Earthquake), we investigate the generation and propagation of static displacements, i.e. coseismic permanent near-field displacements. The static displacements are calculated by double numerical integration after removing acceleration steps from the acceleration signals. The estimated static displacements are totally in agreement with the land deformation measured by GEONET, the GPS network established by the Geographical Survey Institute, despite the fact that our estimation method is extremely simple. It is hoped that scientific studies of this disastrous earthquake will one day lead to a real-time evaluation system for static displacement using strong-motion data. This would be expected to greatly improve the effectiveness of tsunami alert systems, since tsunamis are caused by sea-floor movements during earthquakes.

Key words: Static displacement, strong-motion, KiK-net.

1. Introduction

This short article reports a preliminary evaluation of displacement signals estimated using borehole data provided by the KiK-net (Okada *et al.*, 2004) of the NIED (National Research Institute for Earth Science and Disaster Prevention) for the 2011 Tohoku Earthquake. Given the magnitude of this event ($M_w = 9.0$), the strong-motion records may be quite different from previous records. The generation and propagation of static displacement are evaluated based on near-field recordings.

GEONET, the Global Positioning System (GPS) established by the Geographical Survey Institute (GSI), recorded land deformation up to approximately 5 meters at the Pacific coast of eastern Honshu; in addition, an east-southeast deformation of 5.3 meters and a downward deformation of 1.2 meters were measured at the Ojika GPS site. Such coseismic permanent displacement, i.e. near-field static displacement, and its spatial distribution, can lead to a tilt step in near-field acceleration signals as shown by Pillet and Virieux (2007). Furthermore, local tilt motions due to soil deformation may be induced by strong shaking (Kinoshita, 2008). The simplest method of modeling such tilt motion in the acceleration signals is based on a step increase in acceleration approximated by a Heaviside step function (Zahradnik and Plesinger, 2005; Pillet and Virieux, 2007). This model produces a linearly increasing velocity signal by numerically integrating the acceleration signal. An acceleration step with a finite rise time, of course, causes a tradeoff between the tilt and static displacement signals (Kinoshita *et al.*, 2009). Thus, we evaluated the static displacement by removing the influence of a Heaviside-type acceleration step.

The estimated displacement signals at eleven KiK-net stations indicate the generation of static displacements, which is totally in agreement with the land deformation measured by GEONET and published on the Internet (http://www.gsi.go.jp/).

2. Data and Method

To evaluate near-field displacement signals for this earthquake, we selected strong-motion data recorded at eleven relatively equispaced KiK-net stations in the region between the northern boundary of Iwate Prefecture and the southern boundary of Ibaraki Prefecture, as shown in Fig. 1 and Table 1; the data are provided on the Web site of KiK-net (http://www.bosai.go.jp/). The data for each station correspond to an accelerogram recorded at the top and bottom of a borehole. With the exception of the IBRH20 site, the borehole bottom recordings are used to estimate static displacements. For the IBRH20 site, the surface signal is used since the borehole depth at this site is rather large.

In this study, a conventional method is used for calculating the displacement signal from the acceleration signal (Zahradnik and Plesinger, 2005; Pillet and Virieux, 2007), assuming an acceleration step of the form $aH(t - t_o)$ in the accelerogram, where a, H and t_o represent the amplitude of the acceleration step, the Heaviside step function and the onset time of the step, respectively. The parameters a and t_o are determined from a linearly-increasing velocity signal calculated by numerical integration of the acceleration signal. For example, Fig. 2(b) shows the velocity signal determined from the east-west acceleration signal shown in Fig. 2(a), which was recorded at the MYGH12 site. The dotted line in Fig. 2(b) is a linear fit to the velocity data window between 200 and 300 s, and a and t_o are deter-

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Table 1. Station data used in this study and mean static displacements estimated. Acceleration signals recorded at borehole bottoms at each site are used, with the exception of the IBRH20 site, for which surface signals are used.

	Site code	Site name	Lat. (N)	Long. (E)	Height (m)	Depth of borehole (m)	Static Disp. Eest (cm)	Static Disp. North (cm)	Static Disp. Up (cm)
1	FKSH12	HIRATA	37.2139	140.5736	470	105	164	−48	−25
2	FKSH19	MIYAKOJI	37.4672	140.7261	510	100	188	−39	−45
3	IBRH14	JYUUOH	36.689	140.5518	330	100	110	−2	−29
4	IBRH20	HASAKI2	35.8252	140.7356	6	0	12	13	unstable
5	IWTH08	KUJI-N	40.2658	141.7867	175	100	43	−40	−17
6	IWTH14	TAROU	39.7407	141.9123	200	100	121	−95	−16
7	IWTH21	YAMADA	39.4705	141.9372	13	100	166	−170	−38
8	MYGH03	KARAKUWA	38.9178	141.6412	80	117	368	−201	−72
9	MYGH06	TAJIRI	38.5878	141.0744	20	100	365	−92	−60
10	MYGH10	YAMAMOTO	37.9381	140.8958	18	205	280	−23	−58
11	MYGH12	SHIZUGAWA	38.6386	141.4463	18	102	428	−161	−83

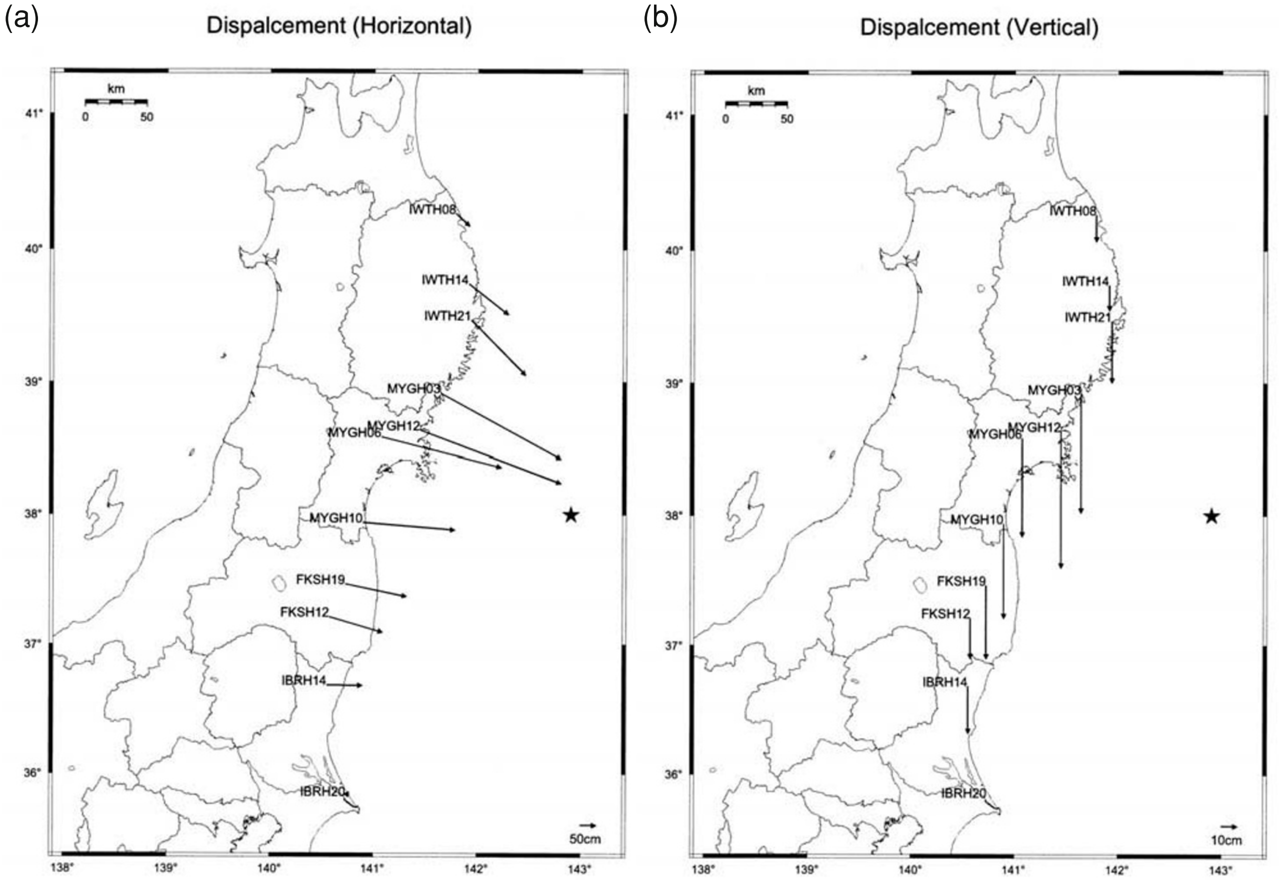

Fig. 1. Locations of KiK-net stations used in this study and estimated static displacements: (a) horizontal direction and (b) vertical direction. These static displacements are mean values calculated from displacement data in the data window from 200 to 300 s.

mined from the gradient of this straight line and its intercept on the time axis, respectively. From acceleration signals compensated for the offset a for $t \geq t_o$, tilt-compensated velocity and displacement signals are calculated as shown in Figs. 2(c) and (d), respectively. As can be seen from Fig. 2(d), a static displacement of about 4 meters occurs in the eastward direction.

3. Results

Figures 3(a), (b) and (c) show the north-south, east-west and up-down components, respectively, of the displacement signals at the different stations. The displacement directions are eastward, southward and downward and the propagation of the static displacement can be clearly seen in these figures. Table 1 and Figs. 1(a) and (b) show the mean values of static displacement calculated from the displacement data window between 200 and 300 s in Figs. 3(a), (b) and (c). Static downward displacements of 0.5 to 1 m are observed at four sites in Miyagi Prefecture as shown in Table 1 and Fig. 1(b). The largest static displacements are in the eastward direction, with a displacement of almost 4 m observed at the MYGH12 site. These results shown in Figs. 1(a) and

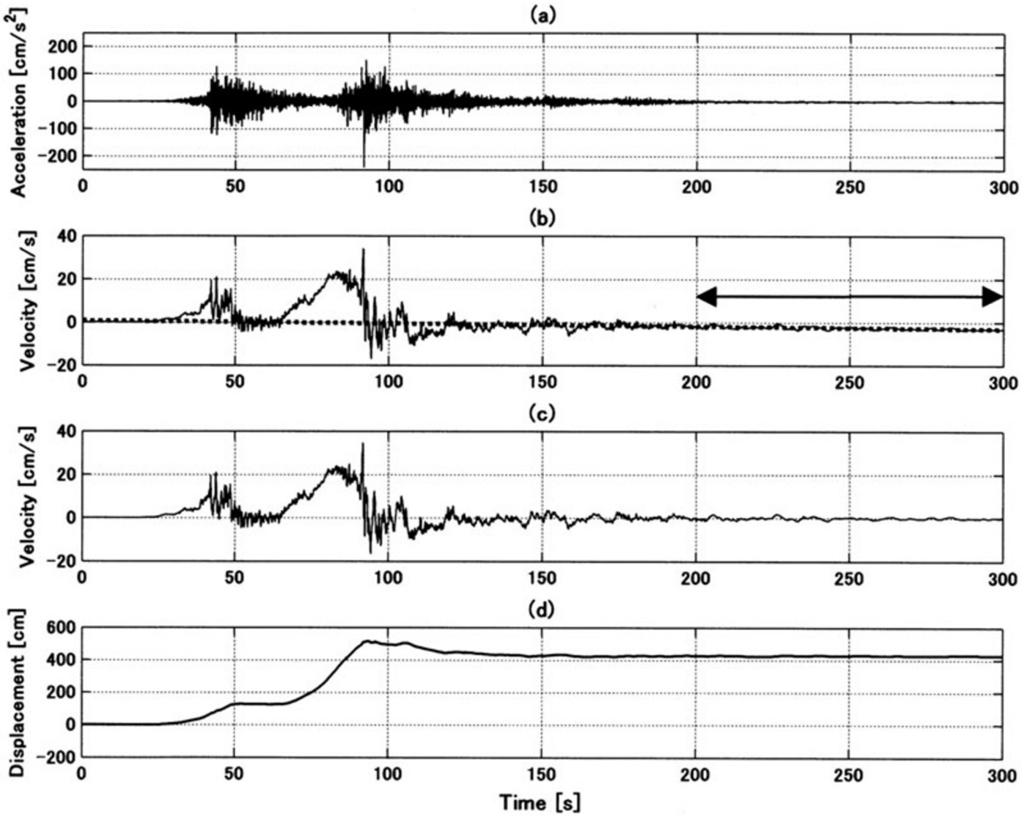

Fig. 2. Example of static displacement estimation: (a) east-west acceleration signal recorded at the MYGH12 site, (b) velocity signals (solid line) calculated by numerical integration of acceleration signal, and regression line (dotted) determined by fitting to the velocity signal in the data window from 200 to 300 s (indicated by arrows), (c) calculated tilt-compensated velocity signal, and (d) displacement signal calculated from velocity signal shown in (c). Coseismic permanent displacement, i.e., static displacement, of approximately 4 m in eastward direction is estimated.

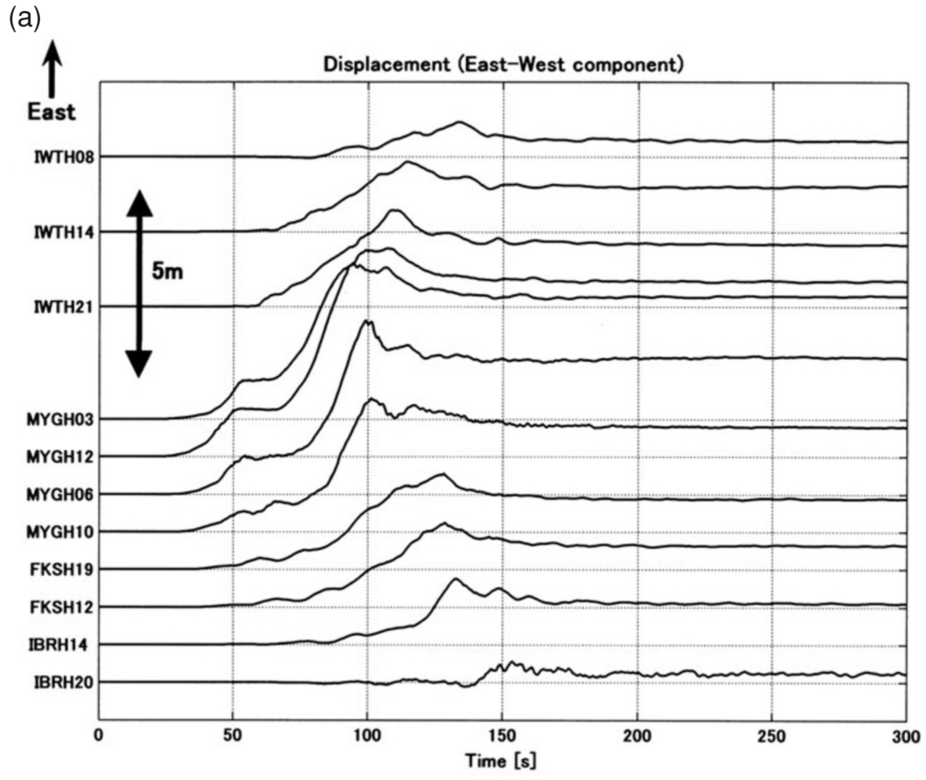

Fig. 3. Displacement signals estimated from borehole acceleration signals recorded at eleven KiK-net stations: (a) east-west, (b) north-south, and (c) up-down components.

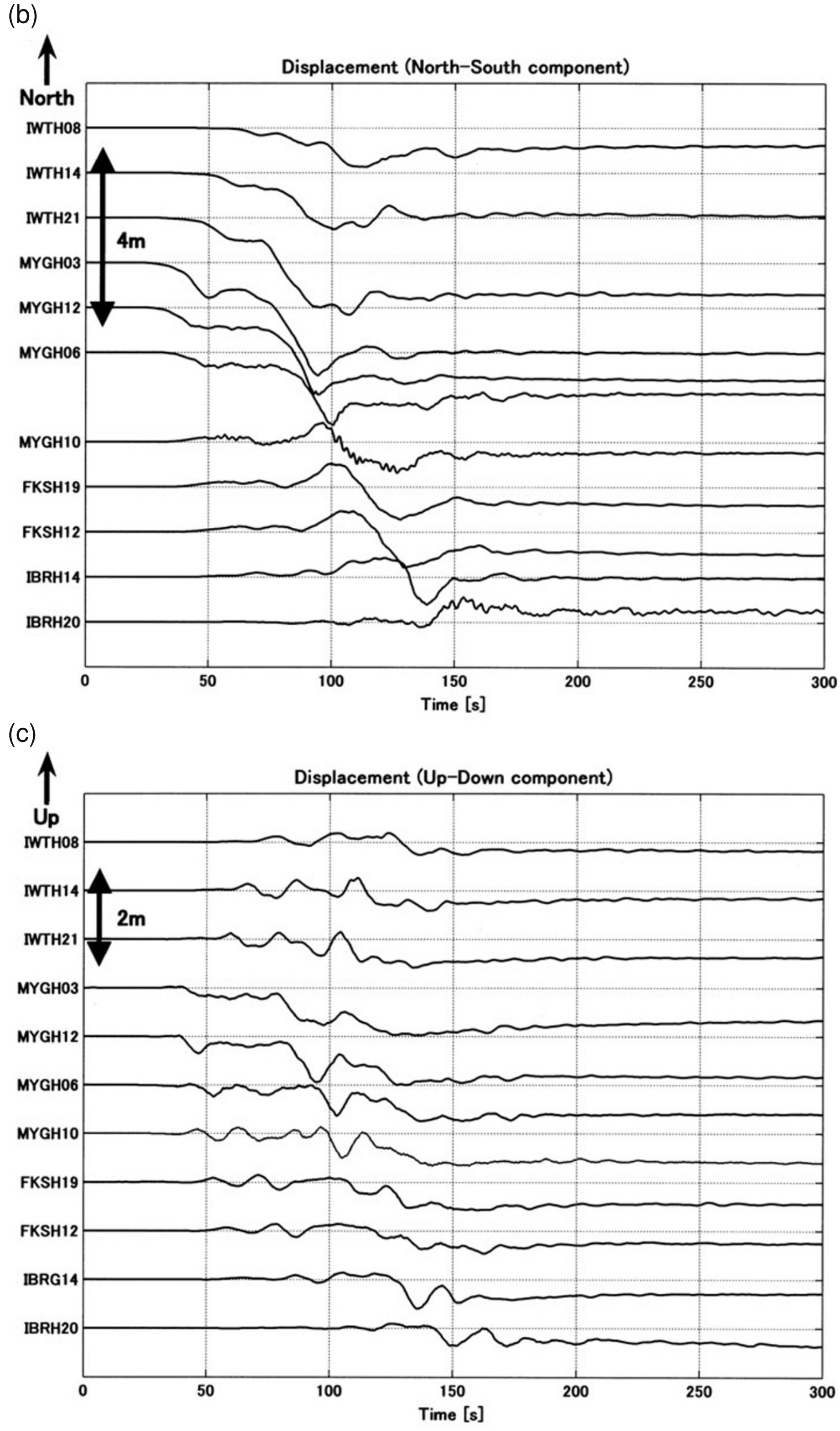

Fig. 3. (continued).

(b) are in full agreement with the GEONET measurements for land deformation just after the earthquake on the whole.

4. Concluding Remarks

As pointed out by Pillet and Virieux (2007), determining the gradient of the velocity signal cannot always be carried out accurately since a data length of 3 min is sometimes too short for a reliable estimation of the gradient, and the maximum pre-event time of 15 s for KiK-net acceleration data may be insufficient for baseline estimation. In the present study, we used a common pre-event time of only 5 s to determine the baseline. However, the estimated static displacements closely match the GPS measurements just after the earthquake. This suggests that the strong-motion data obtained for this earthquake are probably more widely applicable than previous strong-motion records. For example, obtaining the static displacement from strong-motion data before the arrival of a tsunami would improve the reliability of tsunami alert systems, since tsunamis are caused by sea-floor movements during earthquakes. In addition, a knowledge of the downward static displacement may allow the length of the inundation period after the tsunami to be predicted. The possibility of mitigating tsunami disasters provides strong motivation to develop a real-time system for estimating static displacement.

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References

Kinoshita, S., Tilt measurement using broadband velocity seismograms, *Bull. Seismol. Soc. Am.*, **98**, 1887–1897, 2008.

Kinoshita, S., H. Ishikawa, and T. Satoh, Tilt motions recorded at two WISE sites for the 2003 Tokachi-Oki earthquake (M 8.3), *Bull. Seismol. Soc. Am.*, **99**(2B), 1251–1260, 2009.

Okada, Y., K. Kasahara, S. Hori, K. Obara, S. Sekiguchi, H. Fujiwara, and A. Yamamoto, Recent progress of seismic observation networks in Japan—Hi-net, F-net, K-NET and KiK-net—, *Earth Planets Space*, **56**, xv–xxviii, 2004.

Pillet, R. and J. Virieux, The effects of seismic rotations on inertial sensors, *Geophys. J. Int.*, **171**(3), 1314–1323, 2007.

Zahradnik, J. and A. Plesinger, Long-period pulses in broadband records of near earthquakes, *Bull. Seismol. Soc. Am.*, **95**, 1928–939, 2005.

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