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PRECURSOR OF CRUSTAL MOVEMENTS BEFORE THE 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: The crustal movements related with the 2011 Great East Japan Earthquake are described. The maximum displacements of the crust reached some 5 m and 1m in the horizontal and vertical directions, respectively, at some sites. These huge movements of the crust exerted strong influence on tsunami striking and damage of structures. This paper gives detailed information of the crustal movements observed by GEONET before, during and after the earthquake. This paper especially places emphasis on the pre-seismic movements of the crust relating to earthquake forecast.
Key Words: Great East Japan Earthquake, crustal movement, permanent displacement, GEONET, GPS, precursor, pre-seismic, co-seismic, earthquake forecast

INTRODUCTION

On March 11, 2011, a huge earthquake struck the northeastern part of the Honshu island of Japan. The earthquake was officially named "the 2011 off the Pacific Coast of Tohoku Earthquake" by the Japan Metrological Agency, JMA, indicating the region name of its source (JMA 2011). In addition, it was also tagged "the 2011 Great East Japan Earthquake", stressing its damaged area. This paper uses the latter name for convenience. The moment magnitude of the quake was recorded to be 9.0: the largest magnitude of earthquakes occurred in and around Japan. The source fault ruptured in an extremely extensive area of some 500 km long and 200 km wide with a great slip of some 30 m, triggering strong ground motions and tsunami in the Tohoku district, especially three prefectures of Miyagi, Iwate and Fukushima. The fatal victims of death and missing reached nearly 20,000 and various kinds of structures were badly damaged in a vast area of east Japan mainly including the three prefectures. This jolt was especially characterized to cause unpredictable height of tsunami to coastal regions of the three prefectures. Almost all the fatal victims resulted from tsunami. The huge tsunami also crippled the nuclear power plant of the Tokyo Electric Power Company, TEPCO, in Fukushima Prefecture. The earthquake thus induced a kind of paradigm shift to the Japanese society.

On the other hand, the crustal movement is another striking feature related with the earthquake. Due to the enormous dislocation in a huge area of seismic source, the crust of the Japanese islands moved greatly, showing remarkably large permanent displacements of ground. Such crustal movements caused serious social-problems like land use after the earthquake because of the vertically enormous sinking of ground in coastal areas. The heights of tsunami invaded coastal sites in east Japan also had a close relation with the magnitude of the crustal movements. The degree of structural damage due to earthquake motions seems to be similarly related with the movement magnitude of the crust. The permanent displacements of ground thus exerted some influence on various engineering problems. The crustal movements caused by this time's earthquake, moreover, showed quite an interesting feature in time-varying manner. Especially, some precursory movements of the crust indicating the so-called pre-slip of faulting in the seismic source area were clearly detected by GEONET, which is a GPS system for measuring crustal deformation of the Japanese islands, about 3 days earlier than the occurrence of the earthquake. This paper gives detailed information of the crustal movements observed by GEONET, before, during and after the earthquake. This paper especially places emphasis on the pre-seismic movements of the crust and discusses the possibility of earthquake forecast based on monitoring crustal deformation.

OUTLINE OF THE GEONET SYSTEM

In the wake of disastrous experiences of the 1995 Kobe Earthquake, the Japanese government totally changed its attitude regarding earthquake preparedness and established various kinds of scientific systems to carefully monitor earthquake-related phenomena (The Cabinet Office 2010). Included are the K-NET, KiK-net, Hi-net, F-net, GEONET systems and so on (HERP 2011). Among them, GEONET: GPS Earth Observation Network is a total system for measuring the crustal deformation of the Japanese islands using the GPS technique while the others are observation systems for obtaining earthquake motions. The GEONET system was officially established in the year of the 1995 Kobe Earthquake after the integration of the COSMOS-G2 and GRAPES networks that were GPS-based systems until then (GSI 2011). Since then, its observation stations have increased annually and

Fig. 1 Map of observation stations of GEONET

Photo 1 Outlook of the Miyagi-Taiwa observation station of GEONET

GEONET consists, as of 2011, of 1240 GPS observation stations deployed over Japan. Its average station-to-station distance is about 20 km and the Geospatial Information Authority of Japan, GSI, has been controlling each observation station, continuously monitoring deformations of land in the Japanese islands. The collection rate of data from each observation station has also advanced annually and the 1-second rate of data collection has been realized nowadays, that is, it is now possible to grasp the absolute coordinates of the total 1240 observation stations every one second. In addition, the position data at each observation station of GEONET are made widely available to researchers – not just across Japan, but also throughout the world. Fig.1 shows a map of the GEONET observation stations deployed around the epicenter of the 2011 Great East Japan Earthquake. Among these stations, an outlook of one representative station is shown in Photo 1.

GSI has been carrying out three kinds of routine analyses for the GEONET data and the digital data of GEONET resulting from the analyses are available in three different ways: the Q3, R3 and F3 solutions, depending on users' purpose. Among them, the F3 type of data is the most accurate one giving the absolute position of observation station. GSI calls the F3 type of data "the daily coordinates at the GEONET observation station." The F3 data, which were analyzed at all the observation stations at the Japan standard time (JST) of 210000 hours, are available every day throughout the GSI home page. Actually, however, it takes about 2 weeks to carry out the F3 analysis because of various kinds of calculations using accurate information of satellites' orbits, so the F3 data are released about 2 weeks later after the acquisition of their original data by GPS. We downloaded the F3 data throughout the GSI home page and obtained the crustal movements in Japan triggered by the 2011 Great East Japan Earthquake.

CO-SEISMIC CRUSTAL MOVEMENTS DUE TO THE EARTHQUAKE

Under the condition that the F3 data of GEONET are available, it is possible to numerically obtain the co-seismic movements of the crust due to an earthquake by calculating the differences in absolute positions between before and after the event. This method depends on how to set its reference times. We here determined the reference times before and after the earthquake simply so that the occurrence

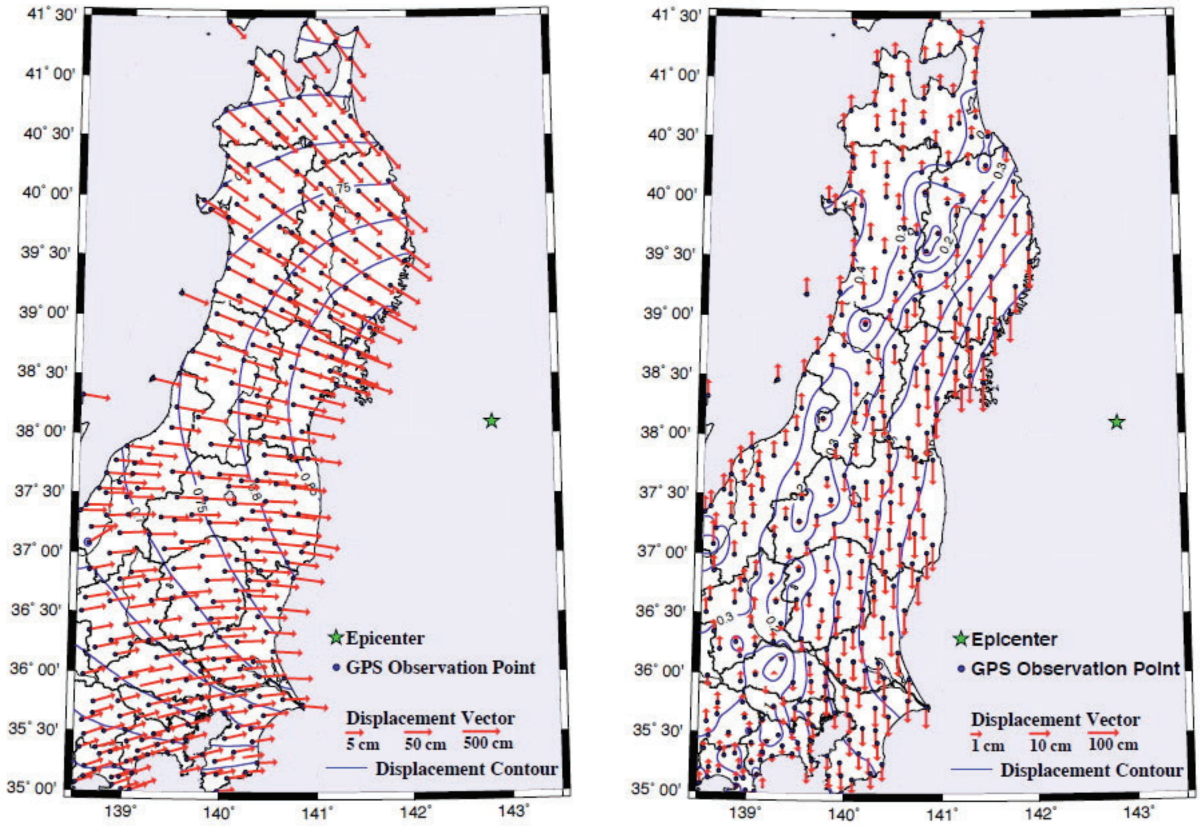

Fig.2 Co-seismic crustal movements obtained by GEONET
(Left: horizontal component, Right: vertical component)

time of the 2011 Great East Japan Earthquake was fully included. The official occurrence time of the earthquake is 144618 hours (JST) on March 11, 2011, so the reference times for the pre- and post-earthquake conditions of the F3 data were set up, respectively, to be 210000 hours (JST) on March10 and 210000 hours (JST) on March 12. We employed a numerical method, which was derived by GSI as an accurate technique, to precisely obtain movement displacements in the three directions of longitude, latitude and height at each observation station of GEONET using the three directional coordinates at these pre- and post-earthquake times. Fig.2 shows maps of distribution for the vector components of displacements on the horizontal and vertical planes obtained by such a method. In Fig.2, the left figure is a map indicating the distribution of displacement vector on the horizontal plane while the right-sided is a similar one on the vertical plane. Both vectors of displacements were plotted in terms of logarithmic scale to clearly express their absolute values that are distributed broadly ranging from a large level of m to small one of cm. It is obvious at a glance in Fig.2 that the Honshu island of Japan moved greatly reaching some 5 m and 1m in the horizontal and vertical directions, respectively, at some sites. The horizontal displacements occurred almost toward the epicenter showing a concentric circle of contour for their absolute values whereas the vertical ones showed sinking and rising of land varying according to epicentral distance. These displacements on both planes, of course, reflect the mechanism of faulting in the source area as shown in later.

The displacements in Fig.2 exerted great influence on various engineering problems. The sinking of land in coastal areas especially has been causing serious social-problem relating to land use because the coastal lands never revert easily to their pre-earthquake levels of elevation. In addition, the displacements of ground seem to have a close relation with other problems resulting from the earthquake. We here present two examples of damage-related problems. One is the correlation between the heights of tsunami and the crustal movements caused in coastal areas. Fig.3 shows a

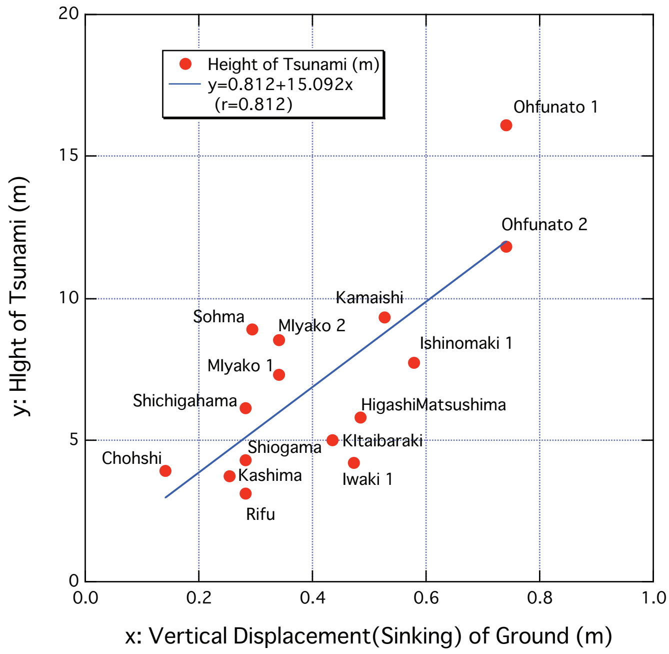

Fig.3 Relation between the tsunami heights and vertical displacements

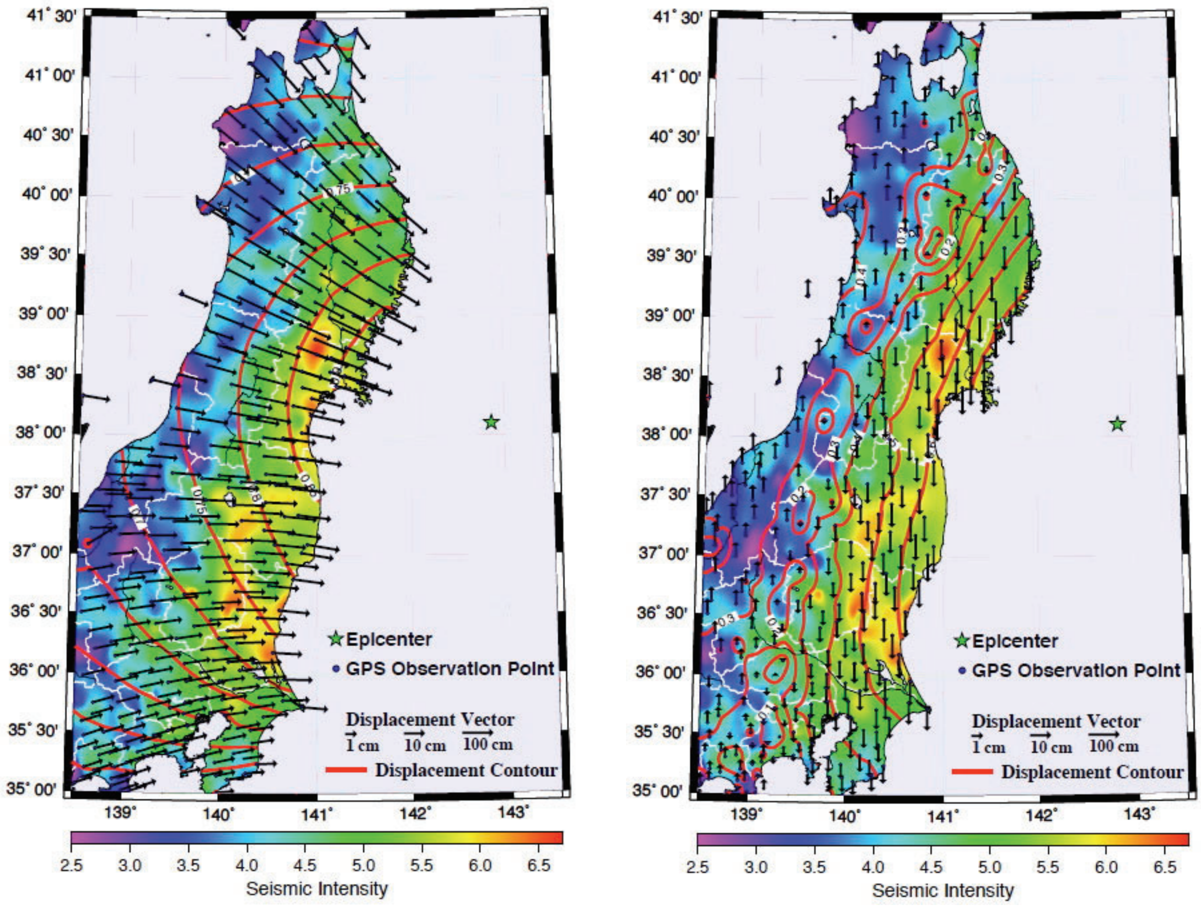

Fig.4 Relation between seismic intensities and crustal movements
(Left: horizontal component, Right: vertical component)

relation between them obtained using some data of tsunami height based on the on-the-spot investigations by JMA (JMA 2011) as well as the data of vertical displacement in Fig.2. Fig.3 indicates that there is a good correlation between the tsunami height and the vertical displacement of the crust. This suggests a possibility of utilizing the crustal movements to issue tsunami warnings predicting their heights at each coastal site when the data of GEONET are available as a real time manner. On the other hand, Fig.4 shows a distribution relation between the seismic intensity and the displacements of the crust occurred during the 2011 Great East Japan Earthquake. The seismic intensities in Fig.4 were estimated using strong ground motions observed by K-NET and KiK-net of the National Research Institute for Earth Science and Disaster Prevention, NIED (NIED 2011). In Fig.4, they are expressed as color image to compare their distributions with both contours of horizontal and vertical displacements of the crust. Strong-ground motions represented by seismic intensity are extremely influenced by local soil conditions, so they have locally peak values apart from the contour lines of the crustal movements that have less influence from local soil conditions. The outline of contours for the vertical displacements in Fig.4, however, conform relatively well to the overall trend of distribution for seismic intensity. A good agreement between both distributions of seismic intensity and vertical displacement of the crust was also found for the 2008 Iwate-Miyagi Nairiku Earthquake (Kamiyama et al. 2011). This might mean that the information of crustal movements given on a real time basis is useful to instantly deduce damaged areas due to an earthquake.

PRE-SEISMIC AND POST-SESIMIC MOVEMENTS OF THE CRUST

Fig.5 shows the time variations of latitude, longitude and height observed over the past 10 years at a representative observation station of GEONET, SHIZUGAWA whose position is shown in Fig.1. Fig.5 also indicates the times of 5 earthquakes giving damages including the 2011 Great East Japan Earthquake during the period. Fig.5 clearly illustrates how great the movements of the crust were brought about by the 2011 Great East Japan Earthquake, compared with the other earthquakes. On the other hand, it is not necessarily clear in Fig.5 how the pre-seismic movements preceded before the 2011 Great East Japan Earthquake because they are extremely smaller than the co-seismic movements due to the earthquake. In order to focus on the pre-seismic movements, the time variations are enlarged in the vertical axes of the three coordinates as shown in Fig.6. We can see in Fig.6 that there are peculiar trends of variations over a long term for each coordinate: that is, there exists a long-term trend of gradually increasing displacement toward south in the latitudinal direction; there exits a log-term trend of gradual movement toward west in the longitudinal direction; and there exists less long-term variation in the height direction. These long-term variations, especially the gradual movements in the latitude- and longitude-directions agree with the Pacific Plate's movements based on the principle of the plate tectonics. In the process of such gradual variations over a long term, Fig.6 also shows some abrupt variations of the crust due to each damage-giving earthquake. These abrupt movements seem to have quite interesting characters: they have a tendency to show zigzag movements reversely varying against the behaviors for the preceding or following earthquakes. In addition, Fig.6 shows a characteristic trend indicating that the above gradual movements over a long term stop and change reversely their directions some time earlier than each damage-giving earthquake. A typical example of such pre-seismic movements is shown in Fig.7 for the case of the 2011 Great East Japan Earthquake. Fig.7 shows the time variations of latitude, longitude and height for the period of about 10 days preceding the 2011 Great East Japan Earthquake. In Fig.7, each day stamp is shown to clearly grasp the daily variations. The time variations of movements differ with each other depending on their directions, but the longitudinal variation indicates remarkably characteristic movements. That is, the longitudinal movement of the crust, which changed its direction from west to east, started to accelerate about 3 days earlier than the occurrence time of the 2011 Great East Japan Earthquake, culminating in the final stage on March 11. Such an accelerated pre-seismic movement of the crust toward the same direction as the main-shock might suggest that a pre-slip of faulting was detected in the GEONET data, meaning that there existed a clear precursor to the earthquake occurrence.

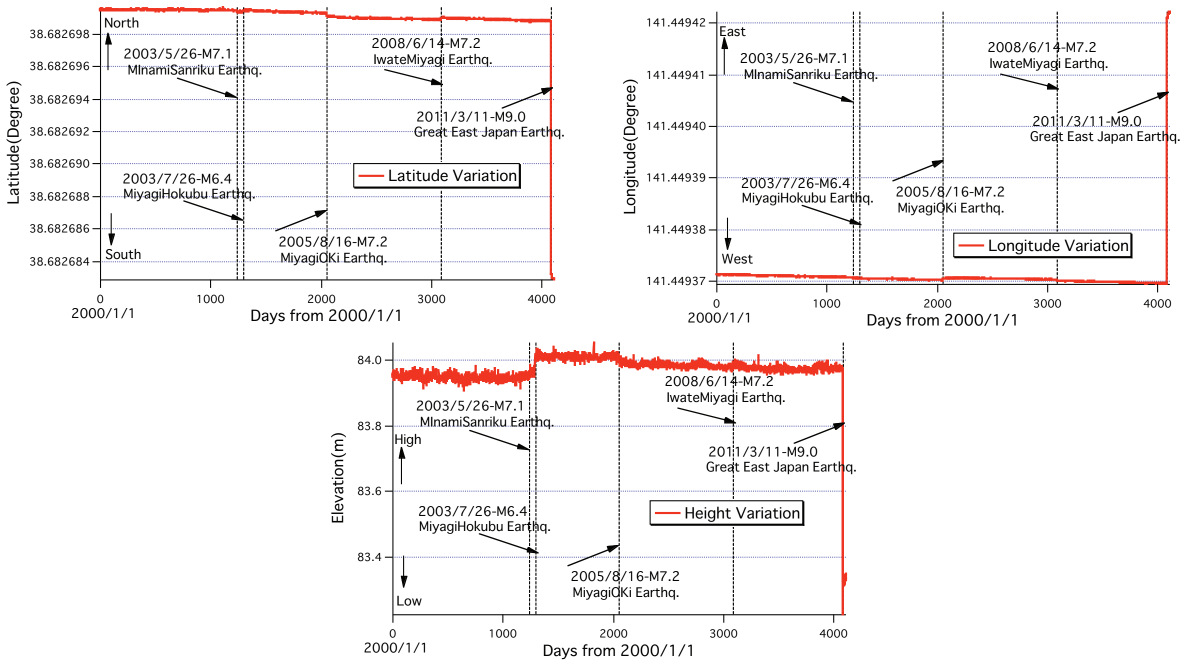

Fig.5 Time variations of latitude, longitude and height over the past 10 years at Shizugawa

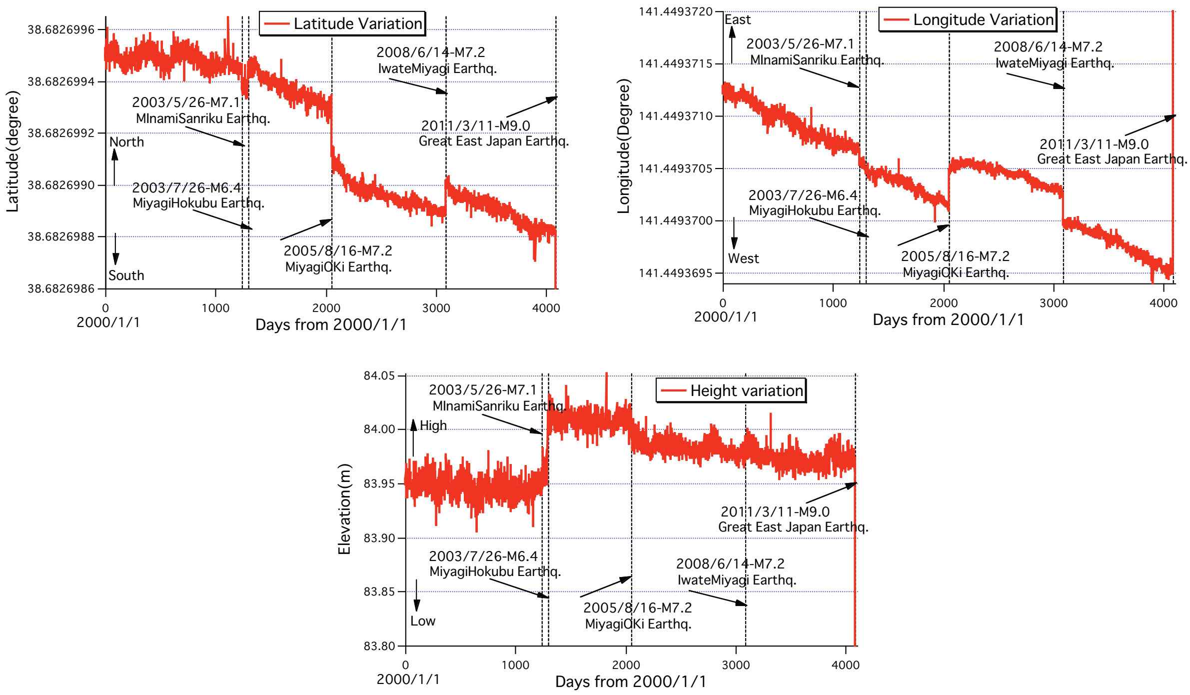

Fig.6 Time variations of latitude, longitude and height over the past 10 years at Shizugawa
(Enlarged in the vertical axes for each figure)

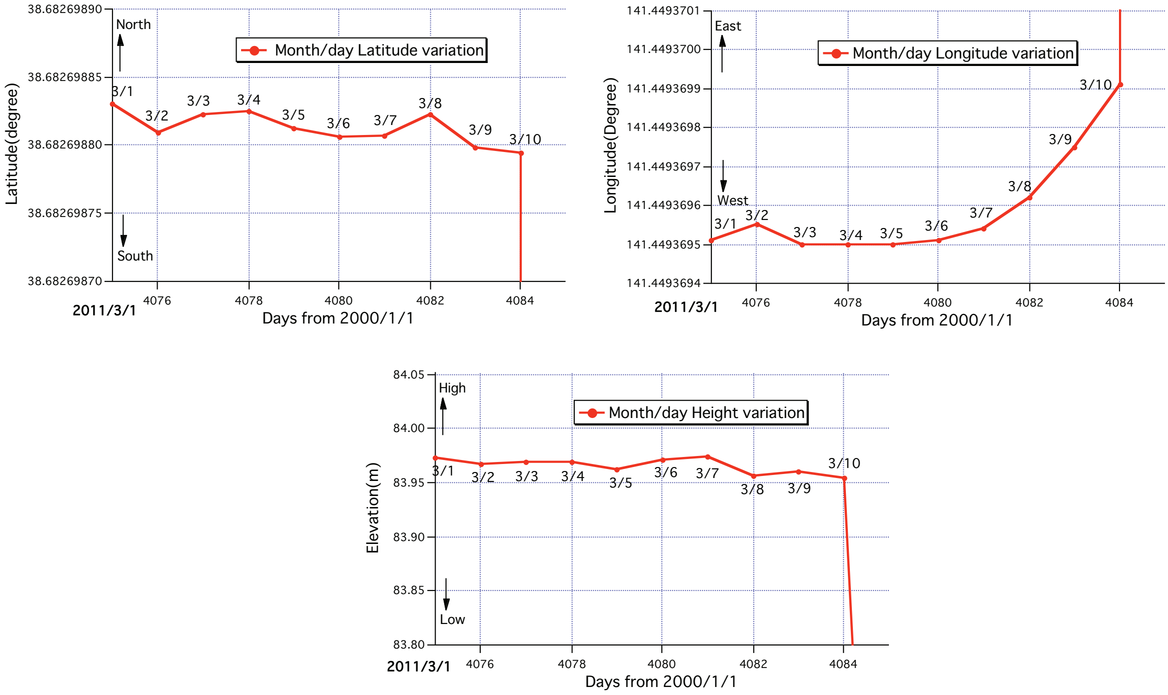

Fig.7 Time variations of latitude, longitude and height over the past 10 days at Shizugawa (Enlarged in the vertical axes for each figure)

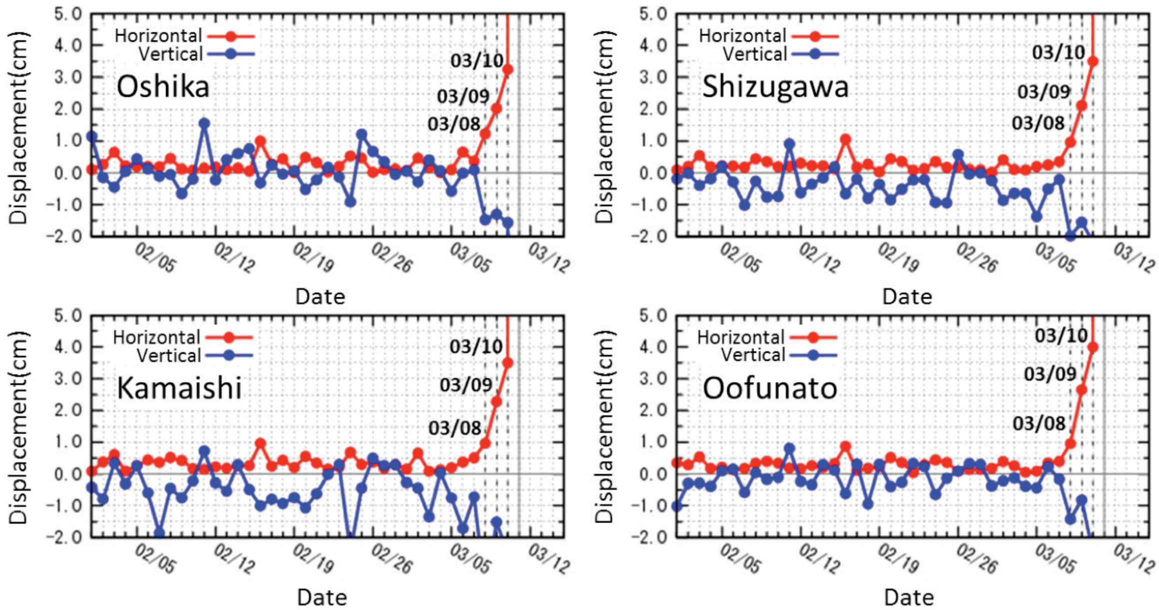

Fig.8 Time variations of crustal displacements at 4 representative observation stations

Fig.7 is a result obtained only at one observation station, SHIZUGAWA. Similar movements of the crust, however, simultaneously occurred at other observation stations, as shown in Fig.8. Fig.8 shows the time variations of ground displacements on both horizontal and vertical planes at some representative observation stations of GEONET lying near the epicenter. The displacements in Fig.8 were obtained by calculating the differences in the three coordinates between each day and January 1,

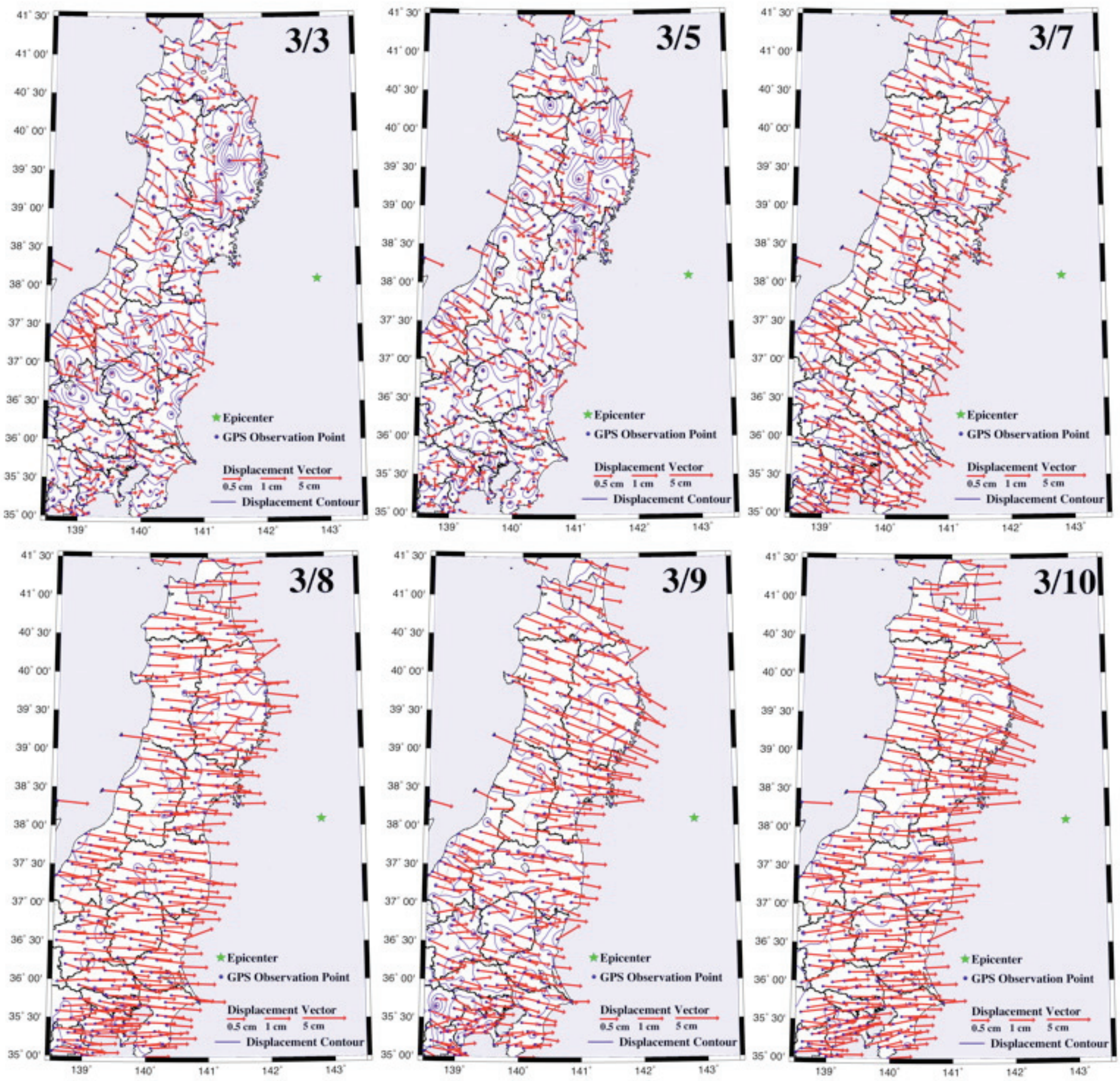

Fig.9 Time variations of displacement vectors (figure in the upper-right corner: month/day)

2011. We can see in Fig.8 that the peculiarly accelerated movements toward east at SHIZUGAWA existed similarly and simultaneously at the other observation stations beginning about 3 days earlier than the occurrence time of the earthquake. In addition to the displacements at representative stations, the crustal movements in a broad area are also shown in Fig.9 as a time variation for displacement vectors on the horizontal plane for a period of March 3 to 10. The displacement vectors in Fig.9 were obtained similarly to the displacements in Fig.8. Fig.9 clearly shows that the crustal movements in the broad region of east Japan, which scattered in various directions until around March 7, started to uniformly point to the epicentral area about 3 days earlier than the occurrence time of the earthquake. Based on these results, we finally concluded that there was a clear precursor of crustal movements indicating the occurrence of the 2011 Great East Japan Earthquake.

On the other hand, the post-seismic movement of the crust is another interest relating to future earthquakes. Fig.10 is the time variations of the crustal movements at the SHIZUGAWA observation station, emphasizing such post-seismic behaviors. The observation at the station was not unfortunately available during a period of March 13 to April 17 because of the effect due to tsunami striking, so Fig.10 lacks plotting data for the period. Fig.10 shows that the post-seismic movements for latitude

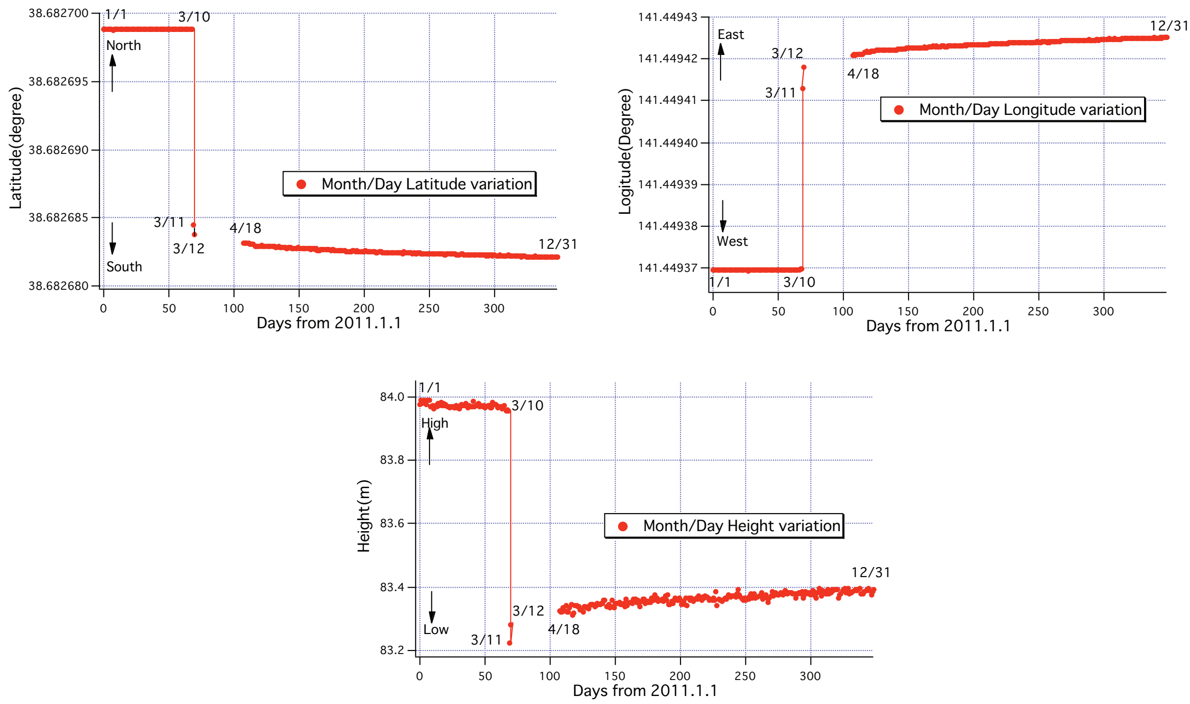

Figure 10　Time variations of latitude, longitude and height from January 1, 2011 to December 31, 2011 at Shiziugawa

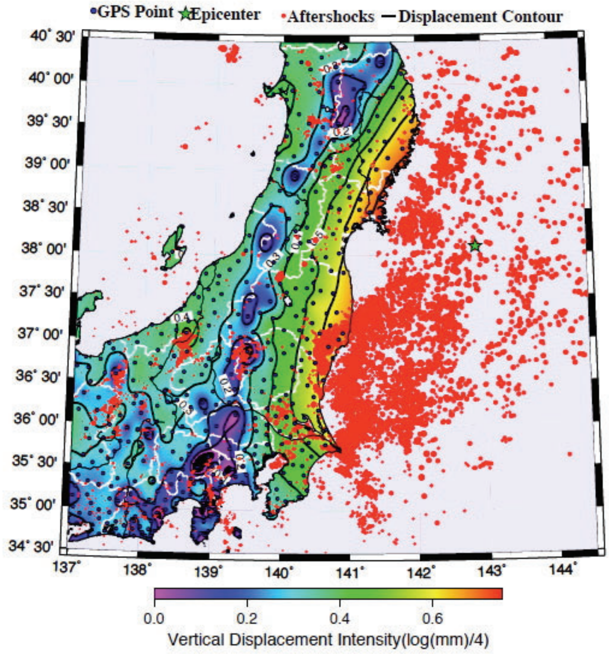

Fig.11　Aftershocks occurred for 1 month after the mainshock and vertical displacement

and longitude have been continuing in the same directions as the co-seismic ones without stopping even 10 months later from the main-shock while the vertical post-seismic displacement reverted its direction from sinking to rising since the co-seismic event. Such post-seismic behaviors of the crust as

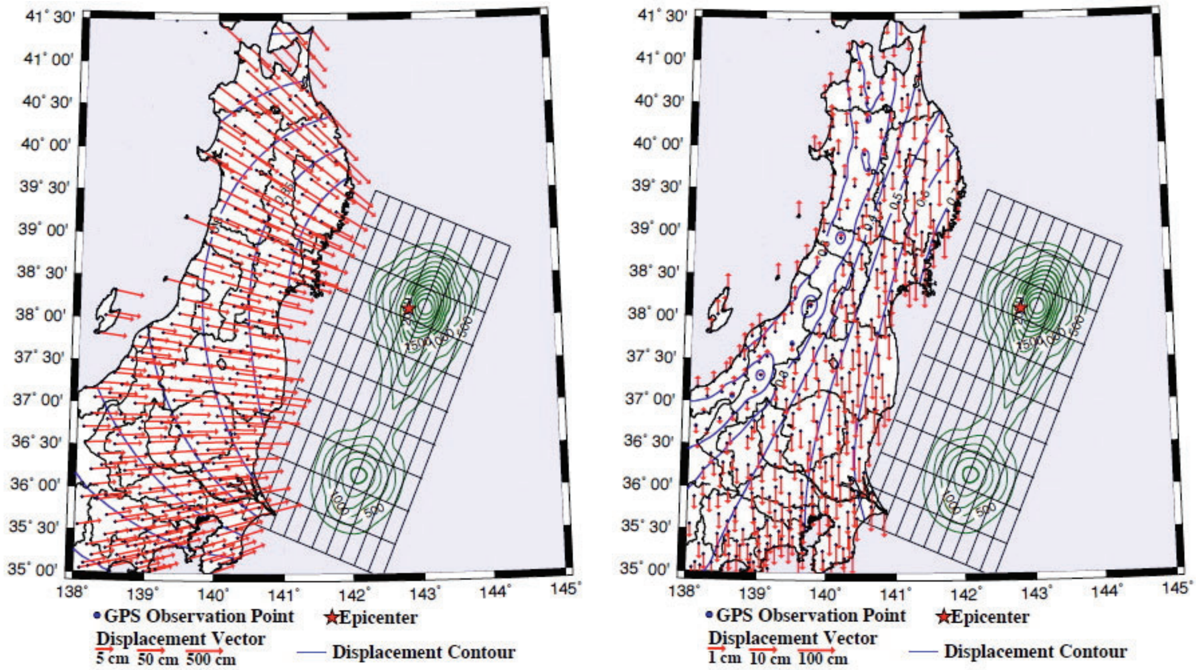

Fig.12 Theoretical estimates of crustal movements by the Okada dislocation theory
(Left: horizontal component, Right: Vertical component)

well as the co-seismic one have influences on the occurrence of various kinds of earthquakes like the so-called induced-earthquake and after-shock. Fig.11 shows a map of earthquakes occurred for a period of about one month from the main-shock. The data of earthquake origins were obtained through the NIED home page (NIED 2011). The co-seismic vertical displacements in Fig.2 are overlaid in Fig.11 by color image together with the contour lines to compare their distributions with the aftershocks and induced-earthquakes. Fig.11 indicates that the induced-earthquakes tend to occur in the inland area characterized by smaller vertical displacements while the after-shocks occur reflecting the seismic faulting in the source area. This means that the co-seismic displacements, especially vertical ones, provide some information about induced- earthquakes and after-shocks.

DISCUSSION ABOUT THE OBSERVED CRUSTAL MOVEMENTS

The precursory phenomena of the crust due to the 2011 Great East Japan Earthquake were clearly detected about 3 days earlier than its occurrence time. The reason that we concluded as the precursor to the earthquake is the following three conditions that are quite similar to the judgment standard stipulated by JMA for the anticipated Tokai Earthquake (Matsumura 2010). Namely, the first reason is that some abnormal and unnatural variations of crustal movement appeared showing explicit difference from the past trends; the second is that such abnormality was simultaneously detected at many sites; and the third is that such abnormality had a trend to accelerate day by day. The precursor of 3 days earlier than the event, which was detected for the 2011 Great East Japan Earthquake, is interestingly consistent, in its time scale, with the abnormal phenomena of the crust experienced during the 1944 Tonankai Earthquake (Mogi 1984). This consistency might be an important hint to promote earthquake forecast. At the same time, such a time scale of precursor as 3 days enhances the necessity of performing analyses for the GEONET data on a real-time basis.

On the other hand, the validity of the observed co-seismic displacements of the crust shown in Fig.2 should be examined in comparison with some theoretical estimates. Fig.12 shows maps of distribution for the displacement vectors theoretically estimated using the dislocation theory by Okada

(Okada 1992). The Okada theory has been coded to many softwares such as the "Coulomb", "3d-def" and so on. We here employed the 3d-def program coded by Gomberg and Ellis (Gomberg and Ellis 1994) to theoretically estimate crustal movements due to the 2011 Great East Japan Earthquake. Many institutes have inferred fault-plane solutions for the earthquake. In reference to the one obtained by JMA, we set a fault plane so that its strike, dip and rake angles are, respectively, 202, 11, and 88 degrees and assumed repeatedly various distributions of slip vector on the plane. Fig.12 shows the distribution of fault slip obtained by such trail-and-error method so as to fit the theoretical crustal movements with the observed ones. The theoretically estimated crustal movements in Fig.12, which are interim versions of estimates, agree relatively well with the observed ones shown in Fig.2. This means that the observed crustal movements obtained by the present study are valid to a degree of scientific acceptance.

CONCLUSIONS

The 2011 Great East Japan Earthquake caused enormously huge crustal movements to the Japanese islands, triggering various engineering problems. At the same time, some pre-seismic crustal movements were clearly detected as a precursor to the earthquake by the GEONET system. They appeared in a form of scientifically doubtless phenomena about 3 days earlier than the main event. This time's experience of detecting pre-seismic crustal movements in case of a huge-scale earthquake provides a good lesson to prepare the strategy for earthquake forecast, though being made clear later after the event. Especially the time scale of 3 days should be emphasized to promote the preparedness for future disastrous earthquakes with great magnitude.

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