13-0002

Seafloor geodesy
- A new challenge for approaching great earthquakes around Japan -

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Abstract. *A new challenge is going on for approaching great earthquakes around Japan such as the nightmarish M9.0 event in 2011; the Japan Coast Guard is conducting measurements of crustal movement on the seafloor close to the plate boundary by applying a technique combining the GPS positioning and underwater acoustic ranging. With this technique, we are successfully gaining important results providing exclusive information for elucidating the plate boundary behavior causing huge earthquakes, which is unable to be clarified only from the terrestrial data.*

Introduction

On 11 March 2011, a huge earthquake (M9.0) occurred off northeastern Japan. A subsequent huge tsunami devastated coastal area, claiming nearly 20,000 lives including those still missing. This is one of the earthquakes occurring on the plate boundary along the major trenches, which Japan has been repeatedly experiencing because of its tectonic location where multiple plates interact with each other.

Rupture planes of such earthquakes lie beneath the seafloor, especially on the side of the Pacific Ocean. According to the theory of plate tectonics, oceanic plates such as the Pacific and the Philippine Sea plates are subducting beneath the continental plate at Japan Trench and Nankai Trough at a rate of several to ten centimeters per year. In such regions, boundary planes between plates are sticking to each other to some degree and a landward crust is dragged with a subducting oceanic plate. This accumulates strain and when it reaches a certain limit, a rupture promptly occurs resulting in a huge earthquake.

To know which part on the plate boundary plane is sticking and to what degree is very important. This information is theoretically in the observed crustal movement around the focal region. In Japan, the dense terrestrial GPS network deployed by the Geospatial Information Authority, which consists of more than a thousand GPS stations, gives significant parts of the observed data for this purpose. However, because there is no data in the offshore area, the resolution on the undersea rupture zone of huge earthquakes is quite poor.

In order to compensate this important blank area of observations, the Japan Coast Guard is conducting measurements of crustal movement on the seafloor close to the trenches around Japan by applying a technique combining the GPS positioning and underwater acoustic ranging (Fujita et al., 2006; Sato et al., 2013a,b). This manuscript will present a brief overview of our seafloor geodetic technique together with some major results so far obtained.

Observation system

Figure 1 shows a basic concept of our observation. The observation system mainly consists of a seafloor unit with four acoustic mirror-type transponders, referred to as “seafloor stations”, and an on-board unit with a GPS antenna/receiver, an undersea acoustic transducer, and a dynamic motion sensor.

The system measures the ranges from the on-board transducer to the seafloor stations through round-trip acoustic travel times, while simultaneously gathering kinematic GPS data. The attitude of the vessel is also measured on board by the dynamic motion sensor, which is used to determine the coordinates of the on-board transducer relative to those of the GPS antenna. The static relative position between the GPS antenna and the on-board transducer was determined by terrestrial surveys while the vessel was dry-docked.

The onsite measurements with this system are made aboard a survey vessel on a campaign basis. In a campaign observation, we conduct acoustic ranging measurements for four seafloor stations in rotation, while the vessel is sailing along pre-determined track lines (Sato et al., 2013a).

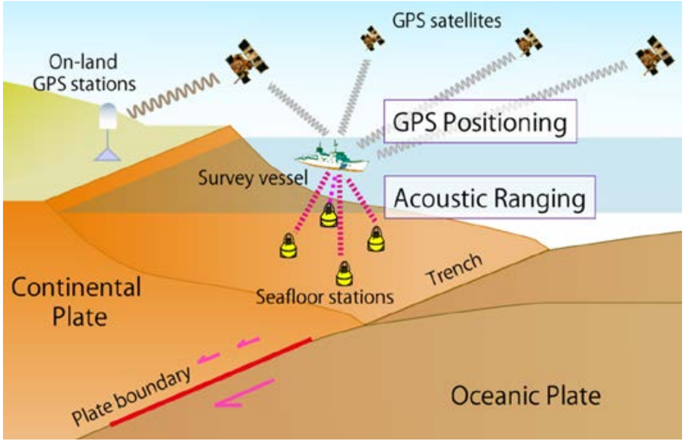

Figure 1. Schematic diagram demonstrating seafloor geodetic system of Japan Coast Guard

In addition, the acoustic velocity profiles in the seawater, which are necessary to transform travel time into range, are obtained from temperature and salinity profilers such as conductivity, temperature and depth (CTD) profilers, expendable CTD (XCTD) profilers and expendable bathythermographs (XBTs) every several hours.

Data analysis

The data analysis basically consists of following three processes (Fujita et al., 2006).

(1)Kinematic GPS analysis: moving positions of the GPS antenna are determined precisely from the phase data obtained on board and at the land reference whose position is precisely known. Though a usual kinematic GPS survey is done for the baseline length less than several kilometers, our positioning requires analysis with a long baseline more than 100 kilometers because the observation area is far offshore and cannot have reference points so close. In this case, effects of spatial inhomogeneity of the ionosphere and troposphere should be large, which must be removed by corrections for the precise positioning.

(2)Acoustic range analysis: the round travel time of an acoustic wave is determined from the transmitted and received signals obtained through the acoustic observation based on the waveform analysis.

(3)Positioning of the seafloor station: the precise position of the seafloor station is determined by combining above two results. A geometrical method is applied to determine the station position based on the least squares approach, which uses the position of the transducer transferred from that of the GPS antenna and the acoustic round travel time. In this process, it is necessary to give acoustic velocity structure in the seawater for the purpose of transformation from the travel time to the range.

The most significant error in our technique comes from the acoustic velocity structure. The performances of observation instruments such as CTD and/or XBT do not come up with our required accuracy of centimeters level. Moreover, it is practically impossible to cover spatial and temporal variations of the acoustic velocity structure by observations. Therefore, making some reasonable estimation and correction of the effective velocity from observed data is necessary, which is a key issue for improving accuracy of the seafloor positioning.

The repeatability of positioning results we have so far attained through various efforts to suppress errors is about 2 cm as a root mean square value.

Major Results

We have deployed our seafloor reference points mainly in two regions on the Pacific side of Japan; one is the region off northeastern Japan along the Japan trench where the 2011 event (M9.0) has occurred and another is the Nankai region along the Nankai Trough, where earthquakes of around M8 have repeated every 100-150 years. In the following, major results in these regions are summarized.

(1) Crustal velocities off northeastern Japan before the 2011 earthquake

Figure 2 shows the crustal velocities obtained off northeastern Japan before the 2011 earthquake (Sato et al., 2013b). The velocity off Miyagi Prefecture, labeled as MYGI and MYGW is 4-5 cm/year relative to the North American plate, which indicates strong coupling around this region.

On the other hand, the seafloor at the seafloor reference point off Fukushima Prefecture, labeled as FUKU, had been moving westward at a constant rate of about 2 cm/year relative to the North American plate from 2002 to 2008. From these results, we can conclude interplate coupling during an interseismic period in this region is significantly weak compared with that off Miyagi Prefecture.

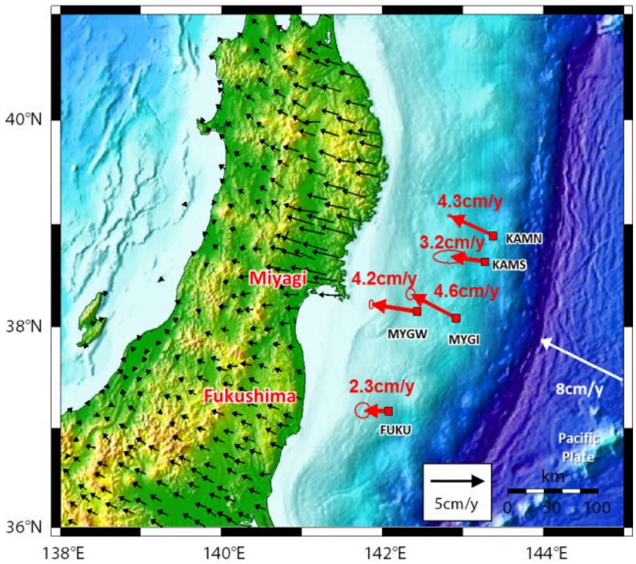

Figure 2. Crustal velocities off northeastern Japan before the 2011 earthquake.

(2) Co-seismic displacements off northeastern Japan associated with the 2011 earthquake

Figure 3 shows the co-seismic displacements associated with the 2011 earthquake (M9.0) off northeastern Japan, which occurred on the plate boundary off Miyagi Prefecture on March 11, 2011 (Sato et al., 2011). Comparison between the positions before and after the 2011 event has exhibited

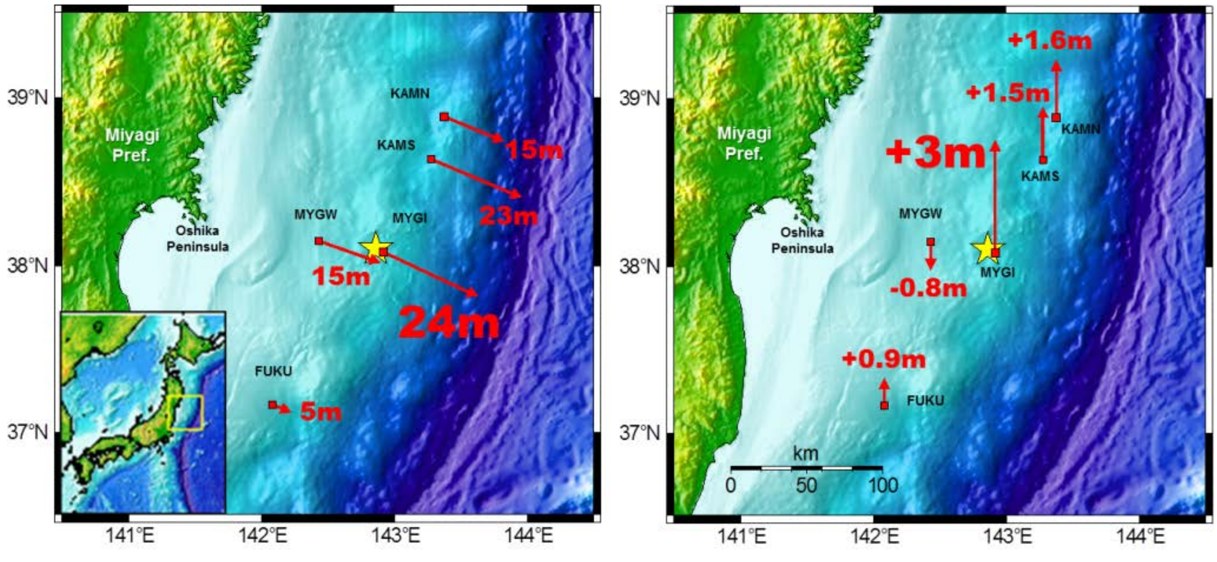

Figure 3. Co-seismic displacements associated with the 2011 earthquake (M9.0) off northeastern Japan (left: horizontal, right: vertical).

huge co-seismic displacements associated with the event in the focal region; the largest amount reaches 24 m east-southeastward and 3 m uplift at MYGI just above the hypocenter, which is more than 4 times larger than those detected on land. Other than MYGI, the co-seismic displacements of 15-23 m off Miyagi Prefecture and 5 m off Fukushima Prefecture have also been detected. These results indicate that the area where co-seismic displacement is greater than 20 m extends at least 70 km toward north-northeast from the epicenter.

From our seafloor observation results together with various studies on co-seismic slip distribution, we can conclude that the co-seismic slip caused by the mainshock occurred mainly close to the trench axis northeast of the hypocenter and the maximum slip was more than 50 m. This amount is almost double to that estimatated from only terrestrial data, exhibiting indispensable role of seafloor geodesy.

(3) Crustal velocities in the Nankai Region before the 2011 earthquake

Figure 4 shows crustal velocities at the six reference points linearly distributed along the Nankai trough based on the 3-4 years data before the 2011 earthquake, which indicates 2-5 cm/year toward west to west-north-west (Ujihara et al., 2012). These movements suggest the strong coupling on the plate boundary as a whole.

A closer look at the results leads us to find notable variation over the region; velocities off the Tokai (TOKE, TOKW) and Shiono-misaki (SIOE, SIOW) areas are larger than those at Kumano-nada (KUMA) and off Muroto-misaki (MURO), though the observation period is yet too short to get reliable results. This variation may demonstrate the difference in the coupling state on the plate boundary depending on the area.

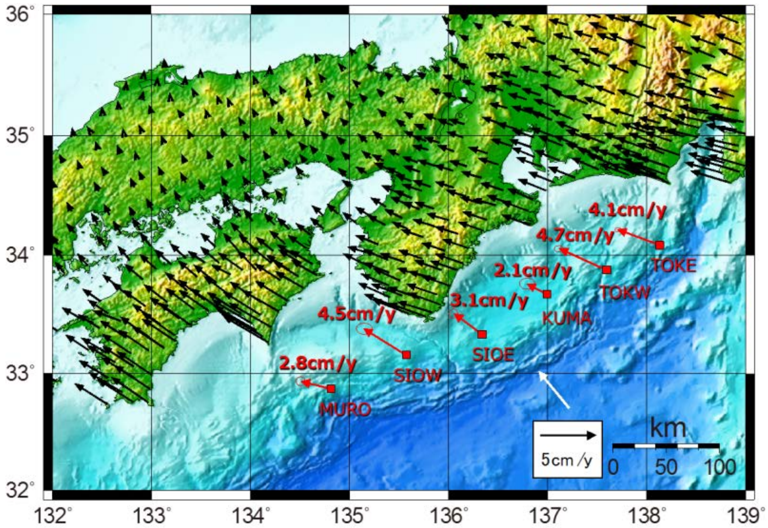

Figure 4. Crustal velocities in the Nankai region before the 2011 earthquake.

Conclusive remarks

In Japan, social concern for huge earthquakes has been pretty high, which was emphasized by the 2011 event. At present, the target area is shifting to the Nankai region which expects next disastrous events in the near future. In this background, the Japan Coast Guard has newly deployed nine seafloor reference points for reinforcing the observation network in this region. This expansion will realize a 2-dimensional coverage over the region, improved from the earlier linear distribution, which is expected to reveal spatial variation of the coupling state more in detail.

Seafloor crustal movements obtained by our technique have successfully demonstrated indispensible roles of seafloor geodesy for the earthquake research. Continuous observations with further development of the technology as well as the infrastructure are essential for approaching huge interplate earthquakes occurring in the sea region around Japan.

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