Chapter 1

The Science of Offshore Earthquakes

Field of Expertise: Marine Geodesy

Motoyuki Kido

Summary

Most researchers did not expect that a magnitude 9 earthquake could occur in the Tohoku subduction zone owing to the lack of an observation technique for crustal stress accumulation beneath the seafloor, a key driver of earthquakes. However, rapid development in surveying techniques of seafloor crustal deformation following the Tohoku earthquake revealed the existence of various tectonic phenomena associated with megathrust earthquakes. The availability of such an observational infrastructure will also assist in accurate early warning against seismic shaking and tsunamis in the future.

Keywords: subduction mega-earthquake, slow slip, tsunami, seafloor crustal deformation, seafloor geodetic network

Introduction

Although earthquakes are found in various tectonic settings, massive magnitude 9 (M9) earthquakes only occur near ocean trenches, where the subduction of an oceanic plate occurs. In a specific area, the recurrence period is thought to range from 500-1000 years. However, they can recur every 10-20 years globally, and must therefore be considered as frequent and shared disaster that threatens humankind in the globalized modern society.

1: Problems Revealed by the Great East Japan Earthquake

What happened?

A large interplate earthquake (M7.3) occurred off the coast of Tohoku, northern Japan, two days prior to the massive M9.0 mainshock on March 11th 2011, which later became known as the Great East Japan Earthquake or the 3.11 Tohoku earthquake. The first M7.3 earthquake is retrospectively recognized as a foreshock. When the Tohoku earthquake struck eastern Japan, we were engaged in preparing an urgent survey on the foreshock in Sendai City, considering its relationship to the impending so-called ‘off-Miyagi’ earthquake, whose average recurrence period of 38 years was nearly up. Had the main shock been delayed by one day, we would have suffered heavily at the port as a result of the tsunami; however, had it been delayed by two days, we might have already been at sea and had an opportunity to obtain valuable on-board data that would have further improved our understanding of the earthquake.

After the Tohoku earthquake, most lifelines stopped, but our lab escaped severe damage from the tsunami as it was located on a hill. Although onshore surveys were immediately resumed, offshore surveys were suspended due to the unavailability of research ships. Initial survey results from across the world showed that a considerable displacement had occurred on a large fault near the trench, further offshore than a typical off-Miyagi earthquake. However, these results were deduced from indirect evidence, such as tsunami height/inundation, seismic waveform, or onshore geodetic data, and direct evidence based on seafloor geodesy was not included. Two weeks after the 3.11 Tohoku earthquake, the first opportunity to conduct a seafloor geodetic survey finally arose. The offshore surveys revealed that the magnitude of seafloor displacement increased toward the trench by up to ~30 meters (Figure 1-1), indicating that the interplate fault had moved several tens of meters. This crucially aided in elucidating the nature of the M9 earthquake.

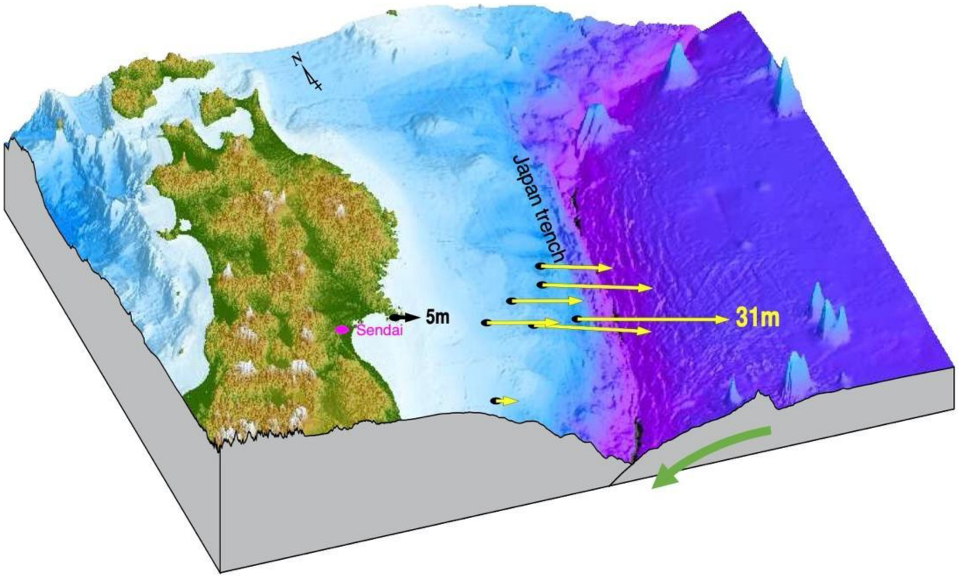

Figure 1-1. Observed seafloor coseismic displacement associated with the 3.11 earthquake (by Tohoku University and Japan Coast Guard)

2: Paradigms Destroyed by the Earthquake

Conventional wisdom and necessary responses

The required observation speed differs greatly between scientific and disaster prevention purposes. For scientific applications, data accuracy and extent are prioritized over speed. However, for disaster prevention, real-time observations are necessary for tsunami warning, and even for risk evaluation of an induced earthquake, a daily, fast operation is most preferable. At the time of the 3.11 Tohoku earthquake, seafloor geodetic surveys were still early in development, and the distribution of existing survey sites was sparse. Therefore, we made much account of repeated regular observations to measure steady strain accumulation for risk evaluation rather than of emergency surveys, which resulted in a significant time lag prior to the first measurement after the earthquake. The essence of an earthquake is the instantaneous release of accumulated strain that concurrently generates additional strain in adjacent areas. This is followed by slow relaxation due to gradually decaying viscous flow and afterslip over several years. It is unfortunate that the data from the initial stage of such a process were missing due to the time lag.

From a scientific perspective, sparse and unevenly distributed observation sites could not resolve strain accumulation near the trench, where little seismic activity of the interseismic period had previously been observed, and slow slip activity had not been well understood prior to the 3.11 event. Recently, slow slip events have been highlighted as their propagation can potentially trigger a large earthquake (Scientific Research on Innovative Areas “Science of Slow Earthquakes”, 2019).

3: A New Approach

Similar to the onshore survey, improving the seafloor geodetic survey is a key task. A GNSS network (Global Navigation Satellite System, including GPS, Michibiki, etc.), called GEONET, consisting of more than a thousand sites, covers the entire Japanese archipelago and yields continuous data in real-time. In contrast, only ~20 offshore sites were in operation around Japan prior to the 3.11 event (Kido, 2013) and the number has only marginally increased to ~60 sites today (Figure 1-2). Furthermore, each offshore site must take a day-long measurement using a research ship to obtain stacked data of a single epoch. Therefore, the time resolution (or frequency) of the data at each site is one month at best, but typically one year at most sites, which is far from the continuous onshore data. Despite such drawbacks, intensive surveys were repeated along the Japan trench after the 3.11 Tohoku earthquake, revealing that the features of post-seismic deformation are significantly different in the epicentral off-Miyagi region compared to the adjacent off-Sanriku and off-Fukushima regions. In the Nankai Trough, where a large earthquake is presumed to occur in the near future, the coupling condition of plate interfaces is evaluated through observations that affect tsunami risk. Furthermore, seafloor geodetic sites were expanded into Ryukyu and Kuril trenches to fill the data gap.

For disaster prevention purposes, numerous seismometers and pressure gauges were installed and linked through seafloor cabling systems (DONET & S-Net) for real-time data monitoring, like the onshore network. This plays an essential role in earthquake and tsunami early warning (Network Center for Earthquake, Tsunami and Volcano, n.d.).

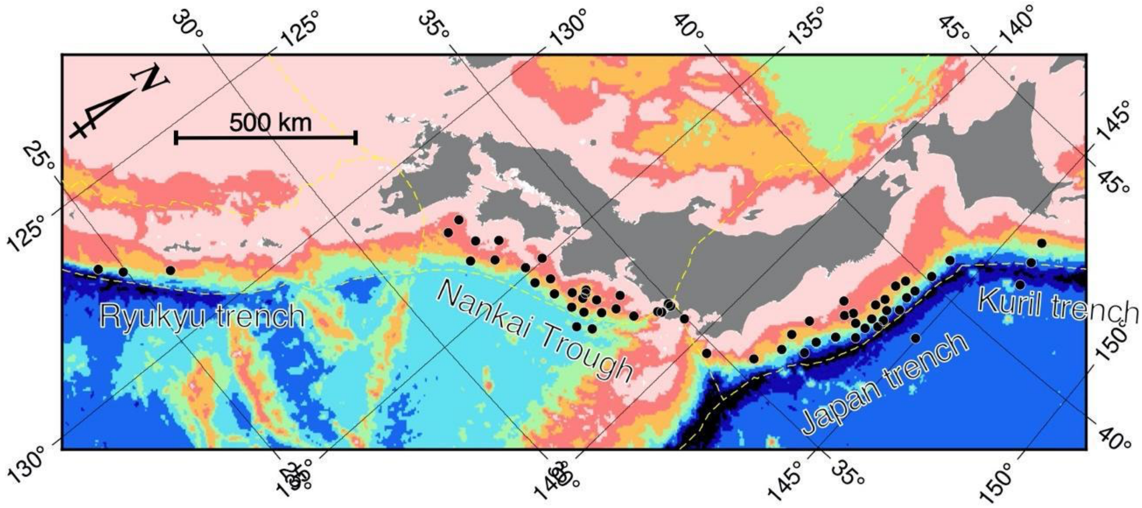

Figure 1-2. Present seafloor geodetic sites (GNSS-acoustic survey)

4: Achievements and the Future

A new approach to disaster science

The rapid development of seafloor geodetic surveys and their infrastructure over the past decade has been remarkable and has greatly advanced scientific knowledge. However, it has not yet progressed to the practical stage for emergency operations in disaster prevention and mitigation applications, unlike the cabled real-time systems. This partially stems from budgetary issues, but mainly from an inverse relationship between the number of sites and survey frequencies due to the limited ship time and human resources. We are engaged in developing an autonomous and unmanned survey platform, such as a marine drone, to overcome this problem. We attached our measurement device to a commercially available barebones platform, called a WaveGlider, and refined the software algorithm for a long-term continuous survey. This system is already in operation (Figure 1-3). The next steps are to develop an effective data transmission system and reduce costs to enable the simultaneous deployment of multi-platform operations.

If numerous platforms can be operated simultaneously, we can monitor seafloor deformation with an incomparably higher frequency than before. This would enable the detection of slow slips with a time constant of several weeks to months. The permanent operation of such a system would enable on-demand measurements immediately after a major earthquake or even during an earthquake as a finite time event. This is what the onshore or cabled system has enabled. Furthermore, improvements in real-time data transmission will contribute to tsunami early warning systems.

Figure 1-3. The sea trial of an unmanned surface platform (WaveGlider).

Conclusion - from the author

Seismology in Japan improved after every devastating earthquake, such as the 1923 Great Kanto Earthquake, the 1995 Great Hanshin-Awaji Earthquake, the 2011 Great East Japan earthquake (the 3.11 event). An M9-class earthquake only occurs once every several hundred years in a particular area; therefore, failure to obtain data during such an event means a permanently lost opportunity to understand the event from a scientific perspective. Hence, we must utilize the lessons learnt from the 3.11 event, i.e., sufficient preparation for earthquakes in both disaster prevention and scientific aspects, through a well-formulated strategy.

References

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