Chapter 10

The Science of Earthquake Shakes

Field of expertise: Earthquake engineering, Strong motion seismology

Susumu Ohno

Translated by Catherine Sachi Kikuchi

Summary

The Great East Japan Earthquake was caused by a complex seismic source with completely different frequency characteristics of seismic waves emitted along the trench and near land. Constructing this type of source model for each frequency range has become an issue in evaluating strong motion of the ground. It is essential to improve the accuracy of the subsurface model for earthquake damage prediction and evaluation of long-period ground motions, and there is a need to construct a reliable model using a large number of observation records.

Keywords: strong ground motion, earthquake damage, long-period ground motion, subsurface structure, source model, earthquake early warning

Introduction

Strong ground motion characteristics can be classified into three main categories: source, propagation path, and ground amplification. In the Great East Japan Earthquake, modeling the source of huge earthquakes, especially the subsurface structure that contributes to the period-dependence and long-period ground motions in distant areas became an issue. The method of early warnings was also reviewed.

1: Problems Revealed by the Great East Japan Earthquake

What happened?

The magnitude of the Great East Japan Earthquake was 9 - it was a very large earthquake that had never been observed in Japan before. As shown in Figure 10-1, tremors of intensity 6 or higher, and in some cases intensity 7, were observed for a long time over a wide area along the Pacific coast of the Tohoku region. In general, short-period tremors with a period of 0.5 seconds or less prevailed in many places, but long-period tremors with a period of several seconds or more prevailed in large plains such as the Kanto, Nobi, and Osaka plains due to the deep and soft subsurface structure (Architectural Institute of Japan, 2012).

Sendai City, Miyagi Prefecture, experienced the 1978 Miyagi Earthquake (M7.4). Comparing the strong-motion records observed at the same location, it was found that the period characteristics were very similar in periods less than 10 seconds, which is related to the shaking damage of buildings and ground. The amplitude was about 30% higher in the Great East Japan Earthquake, which is smaller than the difference in seismic magnitude scale. However, the duration of the earthquake ground motion was much longer (Architectural Institute of Japan, 2012).

The earthquake early warning system, which estimates the epicenter location and earthquake scale based on the observed initial tremors and issues a warning before the major tremor arrives, underestimated the earthquake scale because the scale of the initial rupture that preceded the major slip was small.

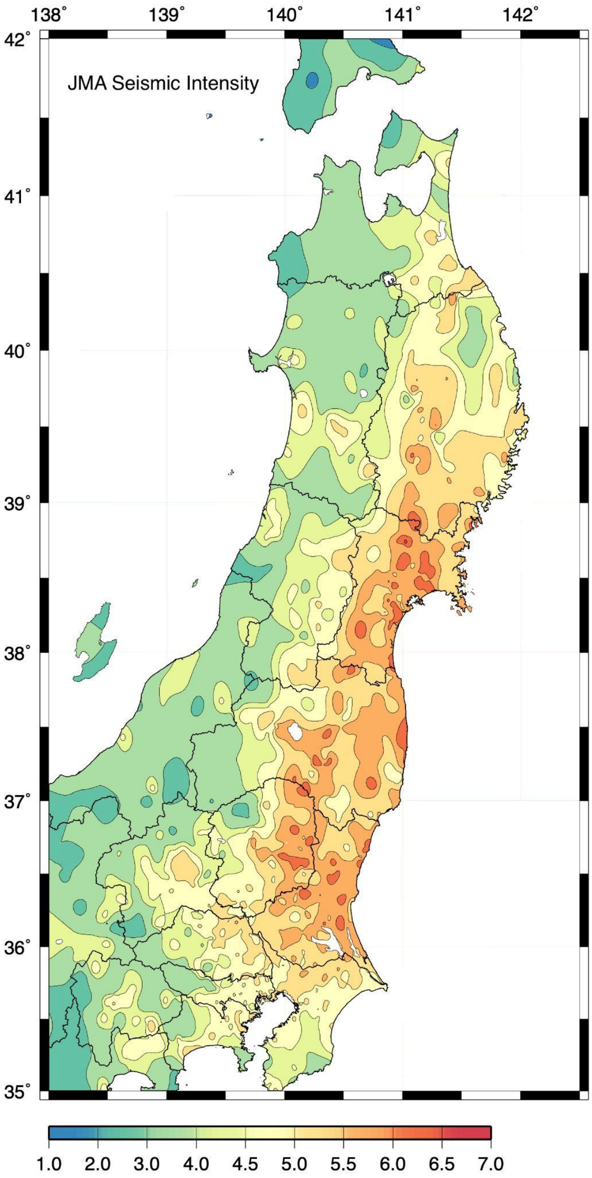

Figure 10-1. Seismic intensity distribution of the Great East Japan Earthquake

The reality of the damage

As for the damage caused by the tremor, in Miyagi Prefecture and other areas close to the epicenter, buildings constructed according to old standards collapsed or were badly damaged and had to be rebuilt, and many old residential areas collapsed. In Sendai City, which also experienced the 1978 Miyagi Earthquake as mentioned above, the areas that experienced major damage in 2011 generally overlapped with that of 1978, suggesting that the effects of ground response were significant. Ground subsidence damage due to liquefaction occurred in a wide area, especially in the Kanto region.

Long-period ground motions prevailed in the large plains, resulting in super high-rise buildings being exposed to tremors for a very long time. At the Sakishima Government Building on the coast of Osaka Bay, 700 kilometers from the epicenter, the natural period of the building resonated with the long-period seismic motion, resulting in shaking of over 1 meter at the top of the building. Even in cases where there was little structural damage that threatened the safety of the building, there were cases where secondary materials called non-structural materials, such as ceilings, partition walls, and equipment sustained significant damage, pointing out the importance of ensuring not only structural safety but also interior safety.

2: Paradigms Destroyed by the Earthquake

Conventional wisdom and necessary responses

The assumed epicentral region and earthquake magnitude have been used in seismic hazard assessments for building design and earthquake damage estimation. Since the 1995 Great Hanshin-Awaji Earthquake, it has not been enough to simply set up a uniform slip on the fault plane to evaluate the ground motions in the period range, which are important for structures. It has been important to model the strong ground motion generation area, which is a place that emits especially strong ground motions, and this kind of source has been modeled for major earthquakes.

In the Great East Japan Earthquake, multiple source regions, which were thought to collapse independently, were linked together, resulting in an earthquake that was much larger than expected. At the same time, there was a large amount of slippage in shallow areas along the trench in the very long period (period: 20s or more), which caused large tsunamis and crustal deformation. On the other hand, in the period that caused seismic damage (period: less than 10s), slippage in deeper areas closer to the land was larger. The existence of such a difference in the period range has been pointed out before, but it had not been incorporated into the scheme of strong motion evaluation because of few observations.

As for long-period ground motions, it has been recognized that they can cause damage even in distant areas due to resonance with structures, as typified by the damage to oil tanks in Tomakomai, Hokkaido, after the 2003 Tokachi earthquake, but it had not been assumed that a super-massive earthquake such as the Great East Japan Earthquake would cause significant shaking of the super high-rise building on the coast of Osaka Bay, 700 kilometers from the epicenter.

Since the earthquake early warning system estimates the epicenter as a point source, it had been noted that there was a problem in its applicability to huge earthquakes where faults rupture over a wide area, but this problem had not yet been solved.

3: A New Approach

In order to incorporate the main slip areas, as described in section 2 above, differ depending on the period into the strong ground motion evaluation scheme, it is necessary to continue studying the modeling for each period. It has also been pointed out that the same strong-motion generating region is not sufficient even for the period that affects the ground motion, and that more hierarchical modeling is necessary. The Great East Japan Earthquake was a huge subduction-zone earthquake, but even in inland earthquakes such as the 2016 Kumamoto Earthquake, there is a difference between a case where the fault does not reach the ground surface (buried fault) and where it appears on the ground surface. In the former case, fast slip in deep areas generates short-period components, while in the latter case, slow slip in shallow areas dominates the long-period components, and the direction of seismic motion dominance is different from the former. The detailed source modeling of the different period ranges and the incorporation of such modeling into the evaluation scheme of ground motions for design are still insufficient due to the small number of observed cases, but the impact on long-period structures is particularly significant, and further studies are necessary.

The accuracy and spatial resolution of the subsurface structure model needs to be improved because the subsurface structure has a significant influence on the evaluation of long-period ground motions in addition to the modeling of the source. However, after the Great East Japan Earthquake, the National Research Institute for Earth Science and Disaster Resilience established a seismic, strong-motion, and tsunami observation network (S-net) for areas in the ocean, and it is expected to improve the accuracy of the subsurface model for evaluating strong ground motions using this network. We must improve the accuracy of the subsurface model for the land areas as well, because the area where the earthquake damage is concentrated often overlaps with the area that the amplification is large in the period (period: more than 1 second for low-rise buildings, longer period for seismically isolated buildings and super high-rise buildings), which has a large impact on structures.

Compared to buildings, the strong-motion observation of the ground has been enhanced by the nationwide seismic intensity observation network and strong-motion observation network since the 1995 Great Hanshin-Awaji Earthquake, but the spatial resolution of the shaking obtained at the time of disaster is still low. In order to improve the spatial resolution of the shaking at the time of the disaster, it is necessary to increase the density of the strong-motion observation itself. And in order to improve the accuracy of spatial interpolation, it is necessary to improve the accuracy and spatial resolution of the underground structure model.

In the case of early warnings for earthquakes, the estimation of the epicenter as a point source was a cause of underestimation, so a method is being developed and applied to estimate tremor wavefields, rather than a method to estimate the epicenter from the initial tremors (Japan Meteorological Agency, n.d.).

4: Achievements and the Future

A new approach to disaster science

In order to obtain accurate ground motion for design purposes and earthquake shaking distributions, we must improve the accuracy and resolution of subsurface models. To do this, subsurface structure modeling has been widely carried out using geophysical exploration and microtremor measurements. We are trying to improve a modeling method of subsurface structures using strong motion observation records based on a joint method, which has advantages such as direct optimization of 3D structure and simultaneous optimization of multiple records.

In addition, since seismic activity in Japan is one of the most active in the world, observation data of strong motion are accumulated every day, and a data-driven approach is possible. In order to improve the accuracy of strong-motion evaluation and shorten the prediction time, we are using machine learning to conduct research on predicting strong-motion for design and immediate shaking (Figure 10-2) (Ohno & Tsuruta, 2018).

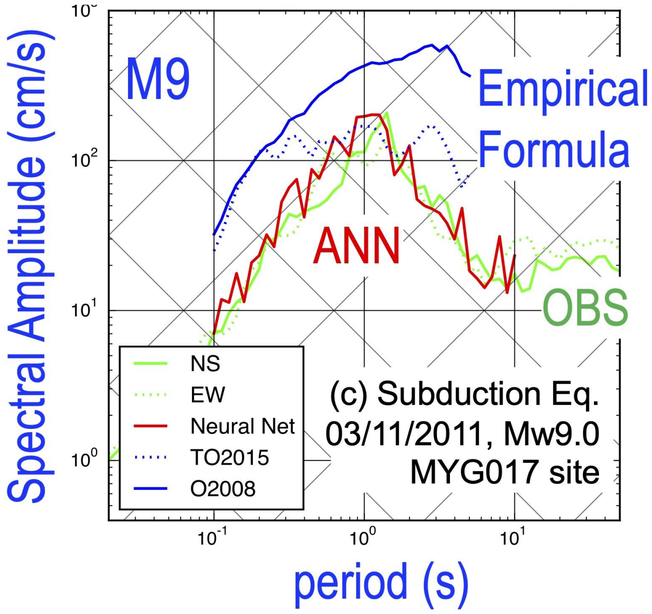

Figure 10-2. An example of earthquake motion evaluation by deep learning (Ohno & Tsuruta, 2018)

Conclusion - from the author

In recent earthquake disasters, such as the Great East Japan Earthquake, areas where damage is concentrated sometimes appear. In most cases, such damage concentration occurs where there are many buildings constructed based on old standards in the area where the ground amplification is high in the period where the structures are likely to shake. It is necessary to understand in advance where buildings are likely to shake based on observation data and reflect it in the ground motion design. It is often pointed out that the evaluation accuracy of strong ground motions is lower than that of a building response, but many records of strong ground motions have accumulated so far, and it is necessary to improve the evaluation accuracy by using data-driven approaches.

References

Architectural Institute of Japan. (Ed.). (2012). *Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake*. Springer. https://doi.org/10.1007/978-4-431-54097-7

Japan Meteorological Agency. (n.d.). *About the PLUM Method*
https://www.data.jma.go.jp/svd/eew/data/nc/plum/index.html

Ohno, S., & Tsuruta, R. (2018). Ground-motion prediction by ANN using machine learning for the Tohoku region, Japan. In *11th National Conference on Earthquake Engineering 2018, NCEE 2018: Integrating Science, Engineering, and Policy* (pp. 5429-5437). (11th National Conference on Earthquake Engineering 2018, NCEE 2018: Integrating Science, Engineering, and Policy; Vol. 9). Earthquake Engineering Research Institute.