Nationwide Field Survey in Japan of the 2011 Off the Pacific Coast of Tohoku Earthquake Tsunami

The 2011 Tohoku Earthquake Tsunami Joint Survey Group

An earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku, Japan, on March 11, 2011. It generated a tsunami 130 km off the northern coast of Japan. The tsunami first reached the Japan mainland 20 min after the earthquake and attacked over 1,300 km along the Pacific coast, inundating over 400 km^2 of land. As of 14 July, estimated fatalities were 16,011 with additional 5,242 missing. This tsunami was the first case that the modern and well-developed tsunami countermeasures faced such an extreme event.

A nationwide tsunami survey has been conducted by joint research groups of 297 researchers among 63 different universities/institutes. Inundation heights and run-up heights were measured at 5,247 points in total. On the Sendai plain, the maximum inundation height was 19.5 m, and the tsunami propagated as a bore more than 5 km inland. Along the ria coast, about 50-200 km to the north of Sendai, the narrow bays caused focusing tsunami and generated the largest inundation heights and run-ups. The maximum run-up height was measured 40.4 m, resulting in the catastrophic destruction of towns and cities.

Key Words : *inundation height, run-up height, Sanriku, ria coast, tsunami disaster countermeasure, watermark, debris*

1. INTRODUCTION

An earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku, Japan, on March 11, 2011, at 5:46 (UTC). The rupture area, assumed to be approximately 450 km × 200 km, generated a tsunami 130 km off the northern coast of Japan. Three minutes after the earthquake generation, severe tsunami warnings were issued by the Japan Meteorological Agency. Then, the tsunami first reached the Japan mainland 20 min after the earthquake and attacked over 1,300 km along the Pacific coast (Figure 1), inundating over 400 km^2 of land. As of 14 July, estimated fatalities were 16,011 with an additional 5,242 missing. The major cause of death was the tsunami and was more than 99% of total causalties in the Tohoku district.

2. TSUNAMI SURVEY AND DISCUSSION

A nationwide tsunami survey has been conducted by joint research groups of 299 researchers among 64 different universities/institutes (see a list of members at the end of this report). The survey began one day after the earthquake in less affected areas and intensified at the end of March after major rescue and relief activities were conducted in the severely affected Tohoku district. Inundation heights (local tsunami height above sea level), and run-up heights (elevation at maximum inundation) were measured at 5,247 points in total and are freely available via our web site (www.coastal.jp/tsunami2011). Inundation heights were collected from watermarks on buildings, trees and walls, and corrected for tidal elevation at the time of tsunami inundation. Run-up heights were determined from the maximum landward extent of debris and seawater marks.

The remarkable feature of this tsunami was not only the magnitude of the event, but also range of inundation areas from urban cities with modern coastal defenses to agricultural lands. On the Sendai plain, the maximum inundation height was 19.5 m, and the tsunami propagated as a bore more than 5 km inland. Along the ria coast, about 50-200 km to the north of Sendai, the narrow bays caused focusing, generating the largest inundation heights and run-ups. The maximum run-up height was measured 40.4 m, resulting in the catastrophic destruction of towns and cities. This tsunami is the third mega tsunami in this decade since Sumatra[1)] and Chili[2)].

Prior to this event, the Tohoku district was assumed to be at high risk to an offshore earthquake and tsunami. The Japanese government reported that a M7.4 earthquake along a 200 km fault offshore of Sendai was expected with 99% occurrence probability within 30 years. The 1896 Meiji-Sanriku earthquake tsunami (M8.2-8.5) occurred causing 21,915 deaths, and smaller tsunamis have occurred every few decades. Thus, earthquake and tsunami disaster countermeasures, such as offshore and onshore tsunami barriers, natural planted tree barriers, vertical evacuation buildings and periodic evacuation training had been introduced to these areas. Hence, we emphasize that the Tohoku district was one of the best prepared areas against the tsunami in the world.

Nevertheless, we must note that the tsunami disaster countermeasures were insufficient against the 2011 event. Tsunami barriers were severely damaged, some concrete buildings were totally destroyed, and maps underestimated the inundation. Some hard protections (e.g. tsunami barriers) may have lessened overall inundation heights, and their effects should be evaluated by detailed surveys and analyses. Both horizontal and vertical evacuations from a tsunami are common in Japan. The vertical evacuation strategies were effective in many areas very close to the epicenter. Although many people survived the tsunami inundation by the planned evacuations, tragically, there were casualties in some areas designated for vertical evacuation due to the extreme inundation levels.

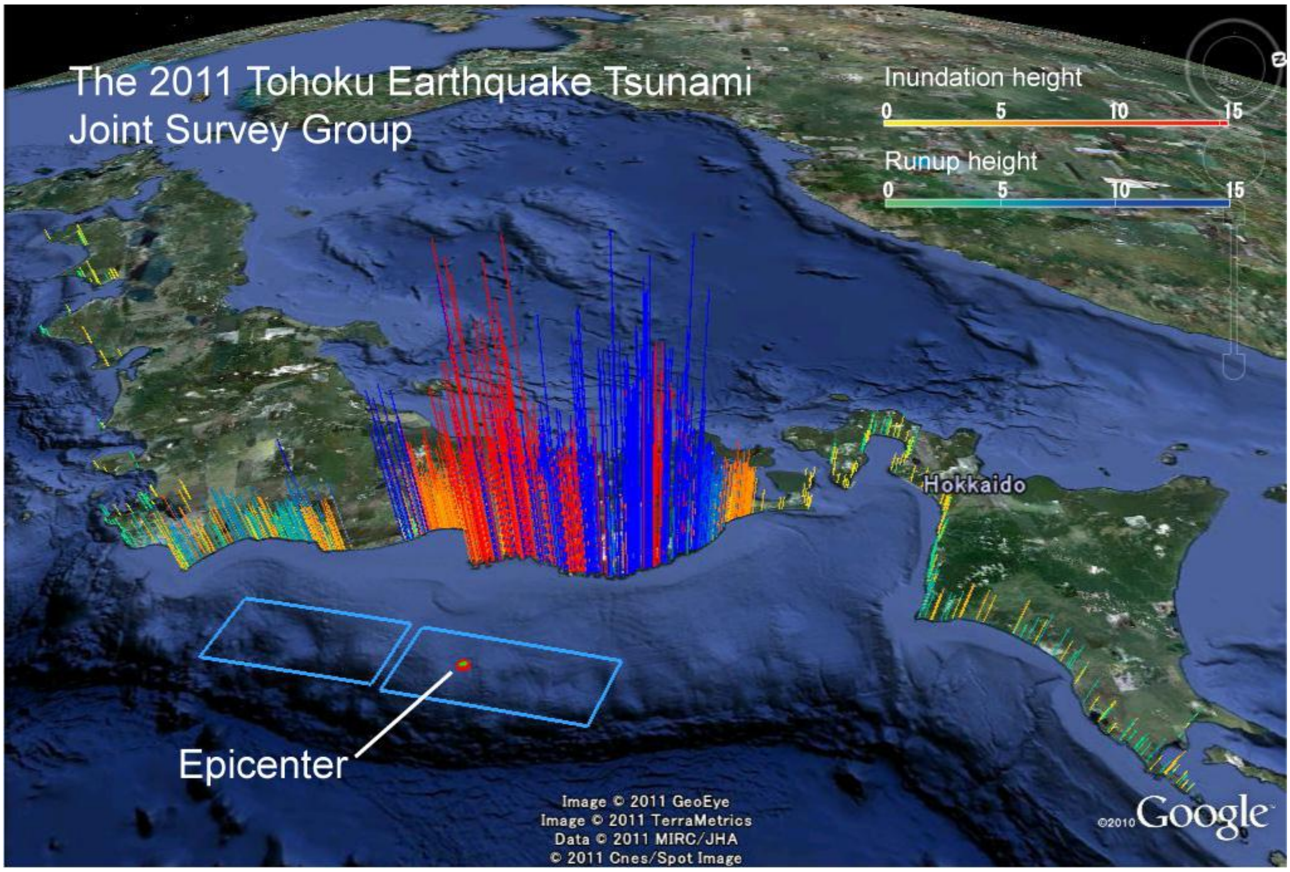

Fig.1 Measured inundation and run-up heights along the Pacific coast of Japan.

3. CONCLUSIONS

The 2011 tsunami was the first case that the modern and well-developed tsunami countermeasures faced such an extreme event. Detailed analysis of the efficiency of different protection schemes and evacuation strategies will be required for the different coastal geometries. One of the most important issues among global communities in natural science, engineering and social science is to learn and to improve tsunami disaster countermeasures from this catastrophic event. Detail data from further surveys and future accurate numerical modeling of the tsunami inundation will help with restorations of the Tohoku district and world-wide planning for tsunami risks.

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REFERENCES

1) Liu, P. L. F., Lynett, P., Fernando, H., Jaffe, B. E., Fritz, H., Higman, B., Morton, R., Goff, J. and Synolakis, C. : Observations by the international tsunami survey team in Sri Lanka, Science, Vol.308, No. 5728, p.1595, 2005.
2) Michelini, A., Lauciani, V., Selvaggi, G. and Lomax, A. : The 2010 Chile Earthquake: Rapid Assessments of Tsunami, Eos Trans. AGU, Vol.91, No.35, p.305, 2010.

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