Survey of 2011 Tohoku Earthquake Tsunami Inundation and Run-up

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Abstract

At 14:46 local time on March 11, 2011, a magnitude 9.0 earthquake occurred off the coast of northeast Japan. This earthquake generated a tsunami that struck Japan as well as various locations around the Pacific Ocean. With the participation of researchers from throughout Japan, joint research groups conducted a tsunami survey along a 2000 km stretch of the Japanese coast. More than 5300 locations have been surveyed to date, generating the largest tsunami survey dataset in the world. On the Sendai Plain, the maximum inundation height was 19.5 m, and the tsunami bore propagated more than 5 km inland. Along the ria coast from about 50 to 200 km north of Sendai, the narrow bays focused the tsunami waves, generating the largest inundation heights and run-ups. The survey data clearly show a regional dependence of tsunami characteristics.

1. Introduction

An earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku, Japan, on March 11, 2011, at 14:46:23 Japan Standard Time (5:46:23 UTC). The rupture area, assumed to be approximately 450 km × 200 km, generated a tsunami 130 km off the coast of Miyagi Prefecture, northeast Japan. This tsunami was the third mega earthquake generated tsunami in this decade; the other two were the Sumatra tsunami [Liu, 2005] and the Chile tsunami [Michelini, 2010]. The tsunami first reached the Japanese mainland 20 min after the earthquake and ultimately affected a 2000 km stretch of Japan's Pacific coast (Figure 1). In the Tohoku district -from north to south- Aomori Prefecture, Iwate Prefecture, Miyagi Prefecture, and Fukushima Prefecture border the Pacific Ocean. Sendai is the largest city in the region. The southern part of Tohoku is relatively flat, especially the Sendai Plain, but the coastal geomorphology of northern Tohoku features ria coasts, which are steep narrow bays. The northeastern part of Tohoku is known as the Sanriku region. The tsunami inundated over 400 km^2 of land. As of July 27, official fatalities were 15,641 with an additional 5,007 missing. The major cause of death was the tsunami, and most fatalities occurred in Tohoku: 57% in Miyagi Prefecture, 33% in Iwate Prefecture and 9% in Fukushima Prefecture, respectively.

Before this event, there was thought to be a high risk of earthquake and tsunami off the Tohoku coast. The Japanese government reported that a magnitude 7.4 earthquake along a 200 km fault offshore of Sendai was expected to occur with 99% probability within 30 years. The 1896 Meiji Sanriku earthquake (Mw 8.2–8.5) and tsunami caused 21,915 deaths, and smaller tsunamis have occurred roughly every 10 to 50 years. 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. Therefore, we emphasize that Tohoku was one of the areas best prepared for a tsunami. Nevertheless, the tsunami disaster countermeasures were insufficient against the 2011 event. Tsunami barriers were severely damaged, some reinforced concrete buildings were totally destroyed, and inundation maps underestimated in several areas.

Avoiding a similar outcome in a future tsunami thus requires better understanding of inundation on land, as well as of tsunami generation and propagation. Numerical simulation is the most important tool for preparing for future tsunamis, and simulation technology has greatly improved in the last few decades [*e.g.* Ioualalen et al., 2007]. Although, tsunami propagation and maximum tsunami height can be estimated with good accuracy up to the shoreline, a simulation of inundation and run-up remains challenging, especially in the case of urban areas. These aspects of local tsunami behavior not only are sensitive to high-resolution bathymetric and topographic data, wave breaking, diffraction, and the other hydrodynamic effects, but also relate to the locations of buildings, streets, and other elements of urban infrastructure [Karlsson *et al.*, 2009]. However, the field data available for understanding and modeling these phenomena are limited because large tsunami events are rare.

The aim of this study is to summarize the results of a post-event field survey for the 2011 Tohoku earthquake tsunami and to provide general understanding of this tsunami disaster. First, an overview of the survey is presented, and tsunami inundation height and run-up height are discussed in general terms. Finally, based on the survey results, regional and bay-scale analyses are presented.

2. Method

2.1 Overview of Survey

Tsunami surveys were conducted by joint research groups with the participation of 297 tsunami, coastal, seismology and geology researchers from 63 universities and institutes throughout Japan (hereinafter denotes the survey group) [The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011]. The joint survey group consists of members from fields of natural science, tsunami engineering, coastal engineering, and tsunami-related research; the survey group was established with the researchers at Faculty of Safety Science of Kansai University and the Disaster Prevention Research Institute of Kyoto University (denotes survey secretariat), because these two universities are located in western Japan, which was largely unaffected by the earthquake.

Surveys began within two days after the earthquake in less severely affected areas I, and surveys in Tohoku began March 25 after the completion of major search and rescue operations in severely affected areas. Until middle of April, teams were assigned to survey locations by the survey secretariat to ensure survey efficiency and to avoid interfering with relief operations. Although the survey areas were wide, the local situation and survey condition were very severe initially. Only thirteen expert survey teams conducted surveys in Tohoku from March 25 to April 8, and thereafter general survey teams including novice members conducted surveys. The survey areas were gradually expanded to all of Tohoku after the middle of April. Maximum inundation heights (local tsunami height above sea level), and run-up heights (elevation at maximum inundation) were measured by the survey group along the Japanese coast except a 30 km zone around the Fukushima Daiichi Nuclear Power Plant.

The height of a tsunami can be defined in three ways: 1) *tsunami height*, the height of the wave until it reaches the shoreline; 2) *maximum water level* (hereinafter, inundation height); and 3) *run-up height*. These three heights are measured from sea level excluding astronomical tide. Inundation height and run-up height were measured within a few centimeters accuracy from watermarks on buildings, trees, and walls by using a laser range finders, a real-time kinematic (RTK) GPS receiver with a cellular transmitter, and total stations. Run-up height was determined from the maximum landward extent of debris and seawater marks. The total number of survey locations was 5300 as of the end of July 2011 (see supplement and web site).

2.2 Inundation dataset and numerical simulations

The survey data were corrected for tidal elevation at the time of maximum tsunami height by using data from tide gauges and from an astronomical tidal database. Because physical damage to tide gauges caused them to fail along the Tohoku coast of Japan, the astronomical tidal database maintained by the National Astronomical Observatory of Japan, NAOTIDEJ, was used for tidal correction in Tohoku. The arrival time of the tsunami was estimated by numerical simulation for Tohoku and was determined by tidal gauge measurements in the other areas. Data on inundation distances were primarily determined by survey measurements. Unmeasured inundation distances were estimated based on the World Vector Shoreline dataset from the U.S. National Geospatial-Intelligence Agency.

A numerical simulation was conducted to estimate the arrival time of the largest tsunami wave by using nonlinear long-wave equation on spherical coordinates. The governing equation is discretized with the explicit leap-frog finite difference scheme. In the spatial domain, all of Japan is covered at a resolution of 0.5 minutes by JTOPO30 bathymetry data. The main purpose of this numerical simulation is to estimate the maximum tsunami arrival time. By using the numerical results and the astronomical tidal database, the astronomical tidal levels were estimated from Aomori Prefecture to Ibaraki Prefecture, where the most of tide gauges were destroyed by the tsunami.

3. Overview of Tsunami Survey Results

Temporal and spatial differences were evident. In Miyagi Prefecture, closest to the epicenter, the first wave was the largest. In Chiba Prefecture to the south, the third wave, arriving three hours after the first, was the largest. This tsunami was remarkable for not only the magnitude of the event, but also the wide variety of inundation characteristics -from urban cities with modern coastal defenses to rural coastal towns and agricultural lands. Local coastal geomorphology also differed substantially across the affected region. Figure 1 shows an overview of inundation heights and run-up heights in Japan and on the Sendai Plain. Effects of local coastal geometries can also be readily seen. The local geomorphology of Sendai City and its suburban areas features a fluvial lowland and flat coastal plain, and the tsunami bore propagated inland. From about 50 to 200 km north of the Sendai Plain, the ria coast area of Sanriku region focused the tsunami waves, generating the largest run-ups and resulting the catastrophic destruction of towns and cities including Taro, Miyako, and Rikuzen-Takata in Iwate Prefecture.

As shown in Figure 1(a), the inundation heights and run-up heights are high from Tokyo to Hokkaido, are separated by a distance that corresponds to two times the distance between Banda Aceh and Phuket Island, approximately. Amplification of tsunami by local topography was observed in many bays and amplification due to trapped edge waves was also observed along plane beaches. The maximum inundation height in Hokkaido was 6.78 m along plane beaches. The maximum inundation heights in the Tokyo Bay area, Shikoku, and Kyushu were 3.41 m, 3.15 m, and 1.0 m, respectively. Tokyo Bay, Shikoku, and Kyushu are located about 390 km, 1000 km, and 1300 km to the southwest of the epicenter. These maximum inundation heights were observed in bays where the local geometry amplified the tsunami wave at the end of the bay.

The Sendai Plain is the most populous area in Tohoku formed by the Abukuma, Natori, and Nanakita rivers. A high spatial density of inundation heights were measured at more than 1000 locations on this plain (Figure 1(b)). The maximum inundation height was 19.50 m, and the mean inundation height near the shoreline was about 10 m. As can be seen in the figure, the tsunami bore propagated inland. The monotonical decrease of inundation height from shoreline can be seen but local geometrical effects including rivers are also significant. The regional analysis will be discussed in Section 4.

4. Spatial Distributions of Inundation Height and Run-up Height

The eastern coast of Tohoku along the Pacific Ocean runs in the north-south direction. Figure 2 shows the projected inundation heights and run-up heights along the latitudinal direction with historical tsunami records from the 1896 Meiji Sanriku Tsunami and 1933 Showa Sanriku Tsunami (Mw 8.4). In the 2011 Tohoku tsunami, the maximum run-up height was 39.7 m at Miyako, which resulted in catastrophic destruction of towns and cities in the ria coast area. The historical records of maximum run-up are 38.2 m in the 1896 Meiji Sanriku Tsunami and 28.7 m in the 1933 Showa Sanriku Tsunami (Figure 2). The maximum run-up height in the 2011 event is similar to that in the Meiji Sanriku Tsunami, but the affected stretch of coastline is several times larger in the Tohoku tsunami than in the Meiji Sanriku Tsunami. Maximum run-up heights of greater than 10 m are distributed along 425 km of coast and maximum run-up heights of greater than 20 m are distributed along 290 km of coast, in direct distance. The size of the 2011 Tohoku tsunami was much larger than assumed; because of the uncertainty of tsunami generation, tsunami modeling based on historical records did not work well. On the other hand, the vertical and horizontal distributions of run-up height are similar or more intense for the 2011 Tohoku tsunami that the 2004 Indian Ocean tsunami [*e.g.* Karlsson, 2009]. Additionally, the blank located about lat 37.5°N in Figure 2 is the 30 km restricted area around the Fukushima Daiichi Nuclear Power Plant. The maximum run-up heights at 30 and 40 km from the nuclear power plant were 16.4 m and 20.8 m, respectively. The run-up heights at the south of Fukushima Daiichi were higher than at the middle of the Sendai Plain, even though Fukushima Daiichi is farther from the epicenter.

The behavior of the tsunami on land shows a clear regional dependence. Figure 3 shows the inundation heights and run-up heights in seven areas as a function of distance from the shoreline. The panels in Figure 3 show data on (a) Hokkaido, (b) Iwate Prefecture, (c) North Miyagi Prefecture, (d) South Miyagi Prefecture, the Sendai Plain, (e) Fukushima Prefecture, (f) Ibaraki Prefecture, and (g) Chiba Prefecture. At locations far from the epicenter (Fig. 3(a) and (d)–(g)), inundation was within 1 km of the shoreline, except at several locations near a river. On the other hand, inundation extended further inland on the Sendai Plain (Fig. 3(c)). Run-up decayed exponential with increasing distance, up to 5 km, from the shoreline; however, much longer tsunami run-ups were measured along rivers. The inundation height in Sanriku (Fig. 3(b) and (c)) is two times higher than that on the Sendai Plain, but inundation did not extend as far inland in Sanriku. The tsunami energy was converted to run-up height rather than to inundation distance in Sanriku. In southern Sanriku (Fig. 3(c)), however, there are several rivers and small fan deltas such as Rikuzen-Takata and Minami-Sanriku. Long run-ups following the rivers were measured even in Sanriku. On average, the characteristics of inundation height decay with increasing distance from the shoreline are different between Sanriku and the Sendai Plain.

A major difference between the 2011 Tohoku earthquake and tsunami and the 2004 Indian Ocean tsunami is the extent of preparation for disaster prevention and mitigation measures. The earthquake resistant planning and construction, and periodic evacuation training had been introduced to Sanriku. By using the high-density database of inundation and run-up information, local tsunami behavior can be assessed and analyzed in inundation areas. As an example, Figure 4 shows local analysis of inundation height and run-up height at Ohtsuchi Bay and Kamaishi Bay in Iwate Prefecture. These bays are located ria-coast area with steep coast, therefore, the locations of survey data are assumed near the coastline for simplicity. The distance between the two bays is about 10 km, and they have water depths of about 50–55 m at the bay mouths. Before the 2011 event, both bays had similar historical run-up records and expected tsunami heights. However, an offshore tsunami barrier was installed in Kamaishi Bay in 2009; this barrier is located 2.3 km from the bay mouth (Figure 4 (b)). The measurement data on inundation height and run-up height will be useful for investigating the effectiveness of tsunami protection during this event. In Ohtsuchi Bay the run-up height is initially 17 m at the bay mouth and maintains a height of 15-19 m to the shoreline, whereas in Kamaishi Bay the run-up height is initially 22 m at the bay mouth, drops to 10 m near the offshore barrier, and remains roughly constant at 10 m up to the shoreline. The significant difference in tsunami protection can be seen between these two geometrically similar bays. This database should enable the effectiveness of hardware protection to be verified for other locations. This work is now ongoing and will be reported in due course.

Furthermore, a notable feature of the data is that local inundation heights and run-up heights differed between neighboring locations. Sea walls, complex shading and diffraction by structures, and debris may play important roles in changing local tsunami behavior. These macro roughness effects on inundation area are also difficult to consider numerically using the standard long-wave equation. Our survey results will be made available as a standard dataset for validating numerical code.

5. Conclusion

This is first major report to present post-event survey results for the 2011 Tohoku earthquake tsunami. This tsunami was the first case where modern, well-developed tsunami countermeasures faced such an extreme event. Among the most important issues in natural science, engineering, and social science for the global community is to learn and to improve tsunami disaster countermeasures based on what can be learned from this catastrophic event.

Accordingly, improving our understanding this event is a vital first research step; this survey dataset provides information on various aspects of tsunami behavior for different geometries and conditions. The major findings from the analysis can be summarized as follows

A) Tsunami inundation heights were observed along a 2000 km stretch of the Japanese coast from Hokkaido to Kyushu; high-quality, high-density tsunami inundation heights and run-up heights were measured.

B) The maximum run-up height in this event was similar to that in the Meiji Sanriku Tsunami but the affected area was several times larger than in the Meiji Sanriku Tsunami. Maximum run-up heights of greater than 20 m are distributed along 290 km of coast, in direct distance.

C) Tsunami inundation extending far inland was observed on the Sendai Plain. The tsunami bore propagated inland more than 5 km from the shoreline.

D) The effectiveness of hardware protection can be investigated by using the measurement data.

However, dynamic information about the tsunami such as velocity or the time course of the inundation process is required to understand this event. Video and the other recorded data will be helpful for estimating the necessary dynamic information. Discussions are now underway on combining survey measurement data, aerial data, and satellite data. Analyses employing these multiple types of data will be important to understand this event and will be necessary to validate numerical models.

We note that both hard (barriers, structures) and soft (evacuation planning) tsunami protections were insufficient in this disaster. Such modern tsunami protections have never faced such an extreme real event. Our preliminary analysis indicates that the hard protection may have resulted in lower overall inundation heights. However, we plan to investigate the effectiveness of different protection schemes and evacuation strategies for the quantitative reduction of damages due to each aspect of a tsunami; to do this, we will analyze locations having different geophysical features, from plane beach to ria coast. Detailed data from future surveys and from accurate numerical modeling of the tsunami inundation will help with the restoration of the Tohoku district and will be useful to apply in coastal regions of high tsunami-risk countries around the world.

Acknowledgements

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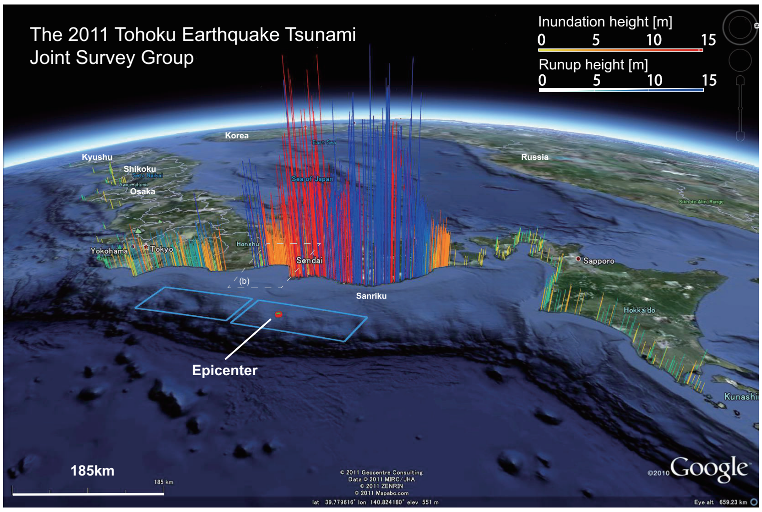
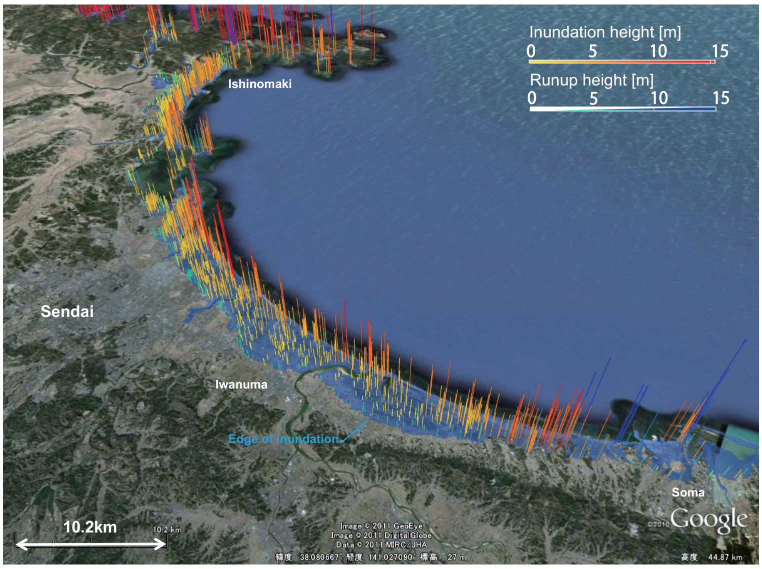


(a) Japan view



(b) Sendai plain

Figure 1. Measured data around the Pacific coast of Japan. Red and blue color bars indicate inundation height and run-up height, respectively.

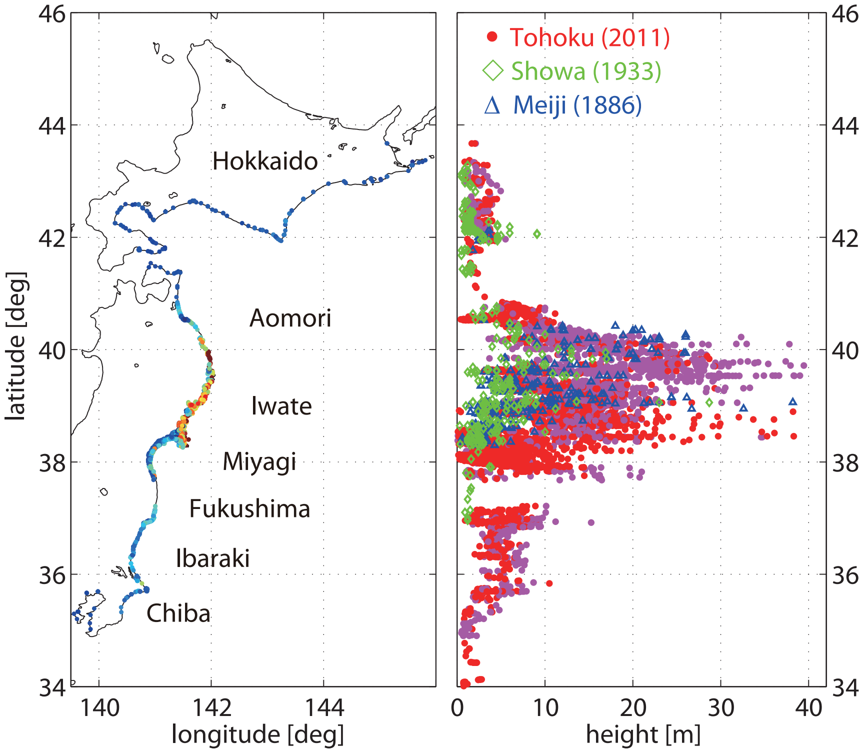
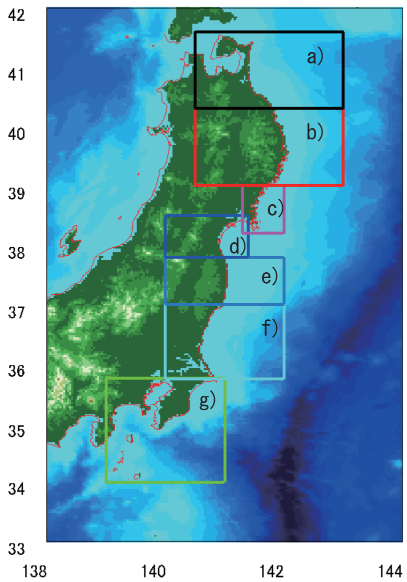
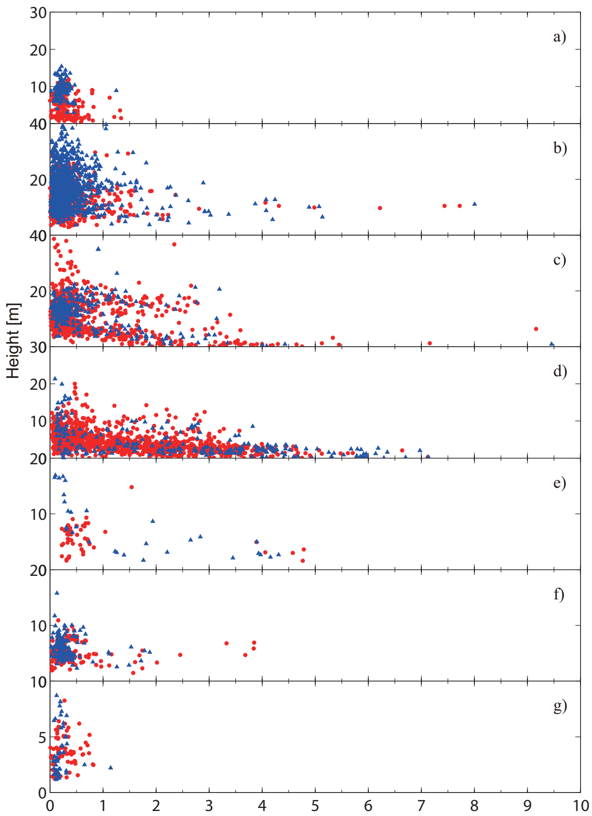


Figure 2. Maximum measured local tsunami heights plotted versus latitude with previous tsunami records (●: Tohoku tsunami, ◇: Showa Sanriku tsunami, △: Meiji Sanriku tsunami)

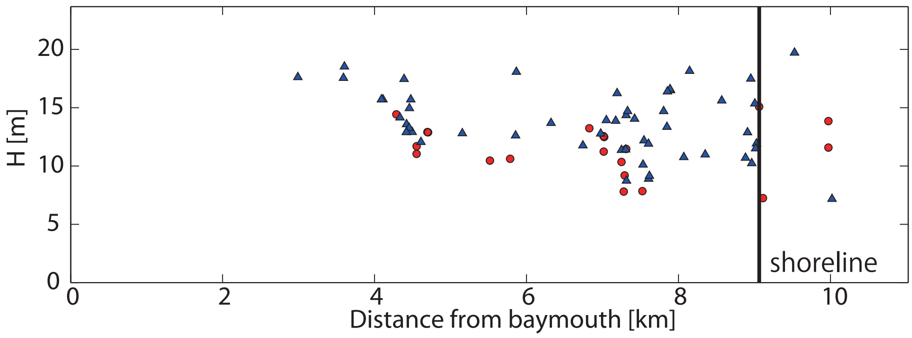


(a) Area of analysis

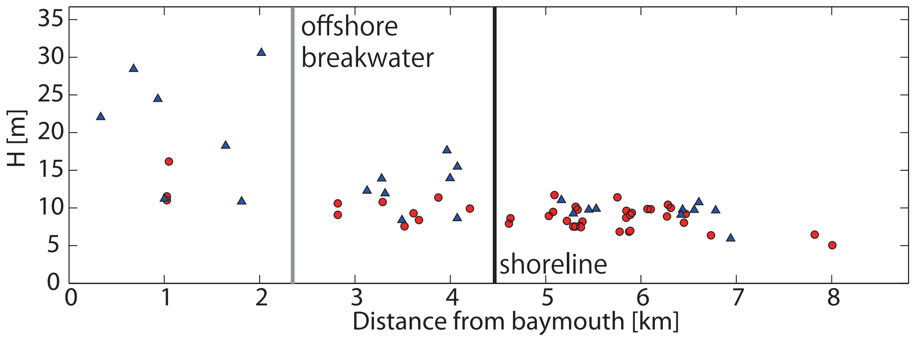


(b) Inundation distance from coast line

Figure 3. Regional analysis of local tsunami height and distance (●: inundation height, △: run-up height)



(a) Ohtsuchi bay, Iwate Prefectre



(b) Kamaishi bay Iwate Prefectre

Figure 4. Example of bay scale analysis of inundation and run-up heights (region (b) in Figure 3) (•: inundation height, △: run-up height)