Relationship between earthquake magnitude and tsunami height along the Tohoku coast based on historical tsunami trace database and the 2011 Great East Japan Tsunami

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The 2011 Great East Japan earthquake generated the largest and most widespread tsunami ever recorded by instruments in Japan. Although such a great earthquake magnitude (*M*) resulting in a large tsunami has already passed, it would be invaluable to learn from a complete dataset ranging from a small tsunami generated by an M7.5 earthquake to a large tsunami, such as the 2011 event, generated by an M9.0 earthquake. Approximately 4,000 points from the historical tsunami trace data and 2,300 measurement points from the 2011 tsunami, representing each area affected along the Tohoku coast, were used to create a plot of tsunami height versus earthquake magnitude. We discovered that the tsunami generated by the 2011 event was not the maximum recorded tsunami height in some areas because of their geographic location and the source areas of the historical tsunamis. Linear regression analysis was performed to find a relationship between the maximum tsunami height and earthquake magnitude. We found that this characteristic could be classified into three regions based on their coastal topography: the Sanriku coast of Iwate, the Sanriku coast of Miyagi and the coastal plain of Miyagi and Fukushima. Historical tsunami data were used to confirm that it was possible to estimate the maximum tsunami height generated by a strong hypothetical earthquake. This new knowledge might be very important for disaster mitigation, planning and warning observations, together with reevaluating tsunami hazard estimations in other areas in Japan, based on these findings for the Tohoku region.

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Keywords: Historical tsunamis, tsunami trace database, 2011 Great East Japan Tsunami, Sanriku tsunami, Tohoku tsunami

1. Introduction

The 2011 Great East Japan tsunami was generated by the most powerful earthquake ever recorded in Japanese history (JMA, 2011). As a result, unpredictably large tsunamis were observed and measured in the majority of places where it struck. The maximum tsunami height of 40.5 m, with an average of 20–30 m, was reported along the Sanriku coast of Iwate and Miyagi prefectures, with average heights of approximately 10–20 m recorded along the coastal plain of the Miyagi and Fukushima prefectures (TTJT, 2012, Mori et al., 2011, Mori et al., 2012 and Suppasri et al., 2012c). The Sanriku coast is well known for its geographic characteristics for wave amplification due to its saw-tooth topography. For example, *M*8 earthquakes generated maximum tsunami heights of 38.2 and 27.8 m in 1896 and 1933, respectively (Yamashita, 2008 and Suppasri et al., 2012c). However, these same earthquakes generated tsunamis less than 5 m height in the coastal plain (Suppasri et al., 2012b and Suppasri et al., 2012d).

Considering these events, it is imperative to understand tsunami height characteristics, which depend on coastal topography, and the relationship between earthquake magnitude and tsunami height. To solve this problem, the Japan Tsunami Trace Database was used for historical tsunamis that were generated by earthquake magnitudes of less than 8.5 and compared with the 2011 earthquake with a magnitude of 9.0. Two challenging questions should be answered: 1) is it possible to estimate a tsunami from the greatest earthquake magnitude ever recorded, and 2) can the analysis results obtained from the Tohoku region be applied to other tsunami-prone areas in Japan?

This study will discuss tsunami height as it relates to earthquake magnitude and coastal topography using data from the 2011 event and other historical events from the tsunami trace database. In addition, this study will explore the potential to estimate the size of the resultant tsunami generated by future major earthquakes using the available historical data from comparatively smaller earthquakes. This understanding will be of considerable importance in preparing for the next great submarine earthquake, such as one within the Nankai Trough along the western part of Japan.

2. Historical tsunami trace database

Information on historical tsunamis, such as earthquake magnitude and maximum tsunami height, can be obtained from the global tsunami event database maintained by the National Geophysical Data Center (NGDC) at the U.S. National Oceanic and Atmospheric Administration (NOAA) (NGDC/NOAA, 2012) and the Russian Novosibirsk Tsunami Laboratory (2012). This study used the Tsunami Trace Database in Japan that was developed in 2007 and released in 2011 based on historical accounts and documents, survey reports and research publications for historical earthquake-generated tsunamis prior to the 2011 Great East Japan event. The database is produced by the Japan Nuclear Energy Safety Organization (JNES) and the Tsunami Engineering Laboratory (TEL) at Tohoku University (TEL, 2012).

The database provides information, such as earthquake magnitude estimated by the Japan Meteorological Agency (JMA) (M_{jma}), tsunami trace level, location (prefecture, city, town and village) and reliability level. Tsunami trace level is primarily comprised of inundation height and inundation depth for some events. The reliability level for tsunami traces and for historical tsunami traces are classified into four levels, A = high, B = moderate, C = low and D = extremely low or only as a reference. In this study, reliability levels A, B and C were selected; level D was also plotted for consideration.

For the 2011 event, this study acquired the necessary information from measurement results performed by the 2011 Tohoku Tsunami Joint Survey Team (Mori et al., 2012). The correspondence earthquake moment magnitude (M_w) was 9.0 (USGS, 2012)). There are two different earthquake magnitudes that will be used in the further analysis and will be discussed here. The database provides M_{jma}, which is available for historical tsunamis but not for large earthquakes, such as the 2011 event, which was estimated by M_w. However, many previous works in Japan, such as studies conducted by the Headquarters for Earthquake Research Promotion (2012), convert M_{jma} to M_w only for inland and shallow earthquakes and assume M_{jma} and M_w to be equal for all other types of earthquakes. Table 1 lists the M_{jma} and M_w of the earthquakes used in the study. It can be observed that for earthquakes over the past 60 years, the difference between the two magnitude scales is approximately 0.1 more or less. Therefore, this study assumes M_{jma} and M_w to be equal, and our nomenclature will use M to mean both magnitude scales.

There were a total of 13 earthquake-generated tsunami events in the study area between 1611 and 2003, with earthquake locations varying from Tokachi-Oki in Hokkaido prefecture, in the north, to Boso Oki in Ibaraki prefecture. This information is summarized in Table 1 along with earthquake source locations; the tsunami-affected areas used in the study are shown in Fig. 1. Tsunami heights from each earthquake event were extracted based on the criteria mentioned above and also considered the amount of tsunami data for each area. The data were divided into 12 areas in Iwate prefecture (Hirono, Kuji, Noda, Fudai, Tanohata, Iwaizumi, Miyako, Yamada, Otsuchi, Kamaishi, Ofunato and Rikuzen−Takata), 5 areas in Miyagi prefecture (Kesennuma, Minami−Sanriku, Onagawa, Ishinomaki and Sendai, from Shiogama to Yamamoto) and one area for the entire Fukushima prefecture. A total of 6,305 tsunami data points and their distributions for each area are shown in Table 2. The selected tsunami heights were then plotted on a horizontal axis and the earthquake magnitude on the vertical axis.

Table 1 List of historical tsunamis in study area and related information

Year	Name	M_{jma}	M_w
1611	Keicho Sanriku	8.1	
1677	Empo Sanriku	7.4	
1677	Empo Boso	8.0	
1793	Kansei Sanriku	8.2	
1843	Tempo Nemuro Oki	7.5	
1856	Ansei Sanriku	7.5	
1896	Meiji Sanriku	8.5	8.3
1933	Showa Sanriku	8.1	8.4
1952	Tokachi Oki	8.2	8.1
1968	Tokachi Oki	7.9	8.2
1993	Off the SW Hokkaido	7.8	7.7
1994	Off the East Hokkaido	8.2	8.1
2003	Tokachi Oki	8.0	8.1
2011	Great East Japan	9.0	

Table 2 Distribution of historical tsunami data used in the study (Number shown in bracket is number of data classified by confidence level D)

Year	1611	1677	1677	1793	1843	1856	1896	1933	1952	1968	1993	1994	2003	2011	Total
Earthquake magnitude	8.1	7.4	8.0	8.2	7.5	7.5	8.5	8.1	8.2	7.9	7.8	8.2	8.0	9.0	
Hirono							16	24	1	2				89	132
Kuji						1	26	31	1	3				117	179
Noda			1			1	10	18		2				71	103
Fudai							17	35		1				51	104
Tanohata							26	28		1				73	128
Iwaizumi							14	23					1	32	70
Miyako	11(2)	8(8)		4(4)	1(1)	1(1)	46	188	2	15	1	1	7	393	678
Yamada	5(5)			4(4)		4(2)	21	55		4			3	104	200
Otsuchi	1(1)			1(1)		4	18	31		2			1	57	205
Kamaishi				7(7)		10	54	108		38			2	228	447
Ofunato	2(2)			3(3)		3	81	217		9		3	2	185	505
Rikuzen−Takata				2(2)		3	35	121		2			3	159	325
Kesennuma				1(1)			119	146		3			1	344	614
Minami−Sanriku						1	102	140		3				162	408
Onagawa				1(1)			20	54		3				70	148
Ishinomaki				3(3)		2	49	143	2	10				590	799
Sendai	2			3(3)				23		2				904	934
Fukushima	3(3)		3(3)	7(7)				11	1	2				299	326

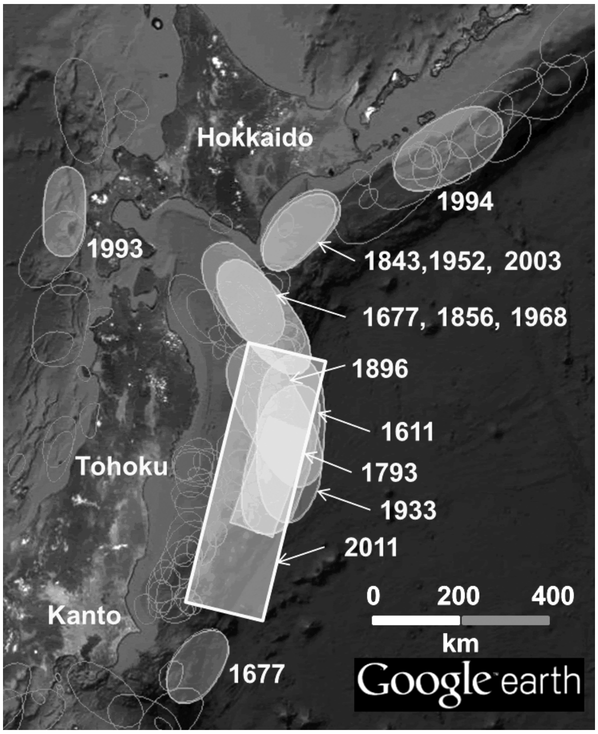

Fig. 1 Location of historical tsunami sources

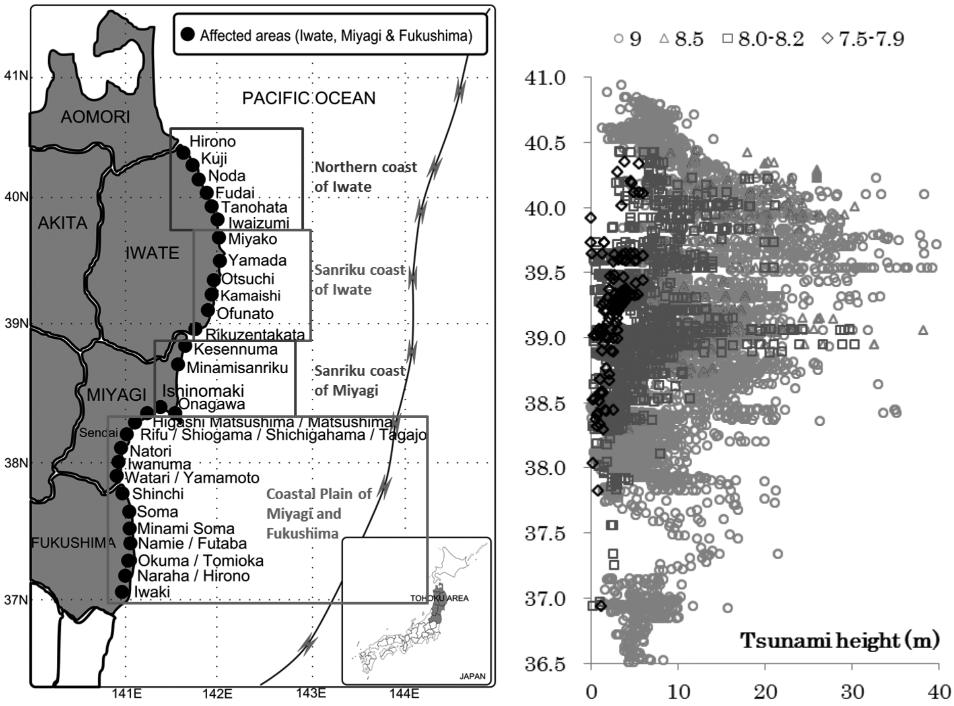

Fig. 2 Location of tsunami affected areas and historical tsunami height distribution

3. Historical tsunami heights along the Tohoku coast

In this study, the Tohoku coast is classified into four regions: the northern coast of Iwate, Sanriku coast of Iwate, Sanriku coast of Miyagi and coastal plain of Miyagi and Fukushima, based on their topography and their impact from the historical tsunamis. Figure 2 shows a distribution of approximately 6,000 historical tsunami heights along the Tohoku coast.

3.1 Northern coast of Iwate

The northern coast of Iwate covers a region comprising six areas from Hirono to Iwaizumi. Because the area is located along the northern portion, tsunami trace data available for this region are primarily from the 1896 Meiji Sanriku and 1933 Showa Sanriku events, with some data from the Tokachi tsunamis in 1952 and 1968. Some results are shown in Fig. 3. In general, the 1968 Tokachi event (*M*7.9) caused a maximum height of approximately 5 m in this area, while the 1933 Showa Sanriku (*M*8.1) and the 1896 Meiji Sanriku (*M*8.5) produced maximum heights of approximately 10–20 m and 20–30 m, respectively. Nevertheless, we found that tsunami heights from the 2011 event (*M*9.0) were not the maximum in some areas, namely, Hirono, Fudai and Tanohata. A probable reason why tsunami heights from the 2011 event were not the highest is that the tsunami source location of the 1896 tsunami was located in the north with a direction parallel to the region. Thus, the tsunami energy was transmitted directly to this region, whereas the energy was almost perpendicular and directed toward the northernmost segment of the region during the 2011 event. Consequently, the maximum tsunami heights in each area might be even greater than that shown in Fig. 3 if a large earthquake similar to the 1896 event occurs in the same area.

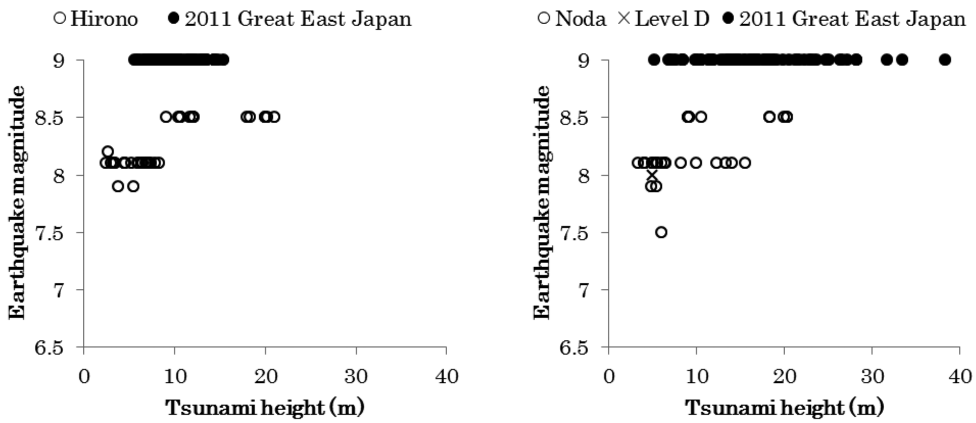

Fig. 3 Plotting of earthquake magnitude and tsunami height in the North coast of Iwate (Hirono and Noda)

3.2 Sanriku coast of Iwate

The Sanriku coast region is comprised of ten areas from Miyako to Rikuzen-Takata in the Iwate prefecture. Tsunami trace data covers historical tsunamis in 1896, 1933 and 1968, similar to the northern coast of Iwate, but with more data for the 1611 Keicho Sanriku (*M*8.1), the 1793 Kansei Sanriku (*M*8.2), the 1856 Ansei Sanriku (*M*7.5) and the 2003 Tokachi (*M*8.0) events. As noted in the previous section, the Sanriku coast is known for its tsunami amplification characteristics because of the ria coast. Additionally, the locations of great earthquakes, such as the events in 1896 and 1933, were also close to this region. Some results are shown in Fig. 4. In general, the *M*7.5 earthquake caused a tsunami of up to 5 m in some areas and a roughly 10–15 m tsunami resulted from the M8.0 quake, excluding Ofunato and Rikuzen–Takata where the tsunami reached 25–30 m. The 1896 Meiji Sanriku event (*M*8.5) generated a maximum tsunami height of up to 20 m in locales from Miyako to Kamaishi and from Kesennuma to Ishinomaki. Nevertheless, the maximum tsunami height from the same [1896] event in Ofunato and Rikuzen–Takata reached 30–40 m. Finally, the 2011 earthquake (M_w 9.0) generated a maximum tsunami of 30–40 m and represents the maximum tsunami height in most areas. Based on these results, areas in Ofunato and Rikuzen–Takata were particularly affected by greater tsunami heights from the same earthquake event, due to their location and direction, compared with other historical tsunamis in the region.

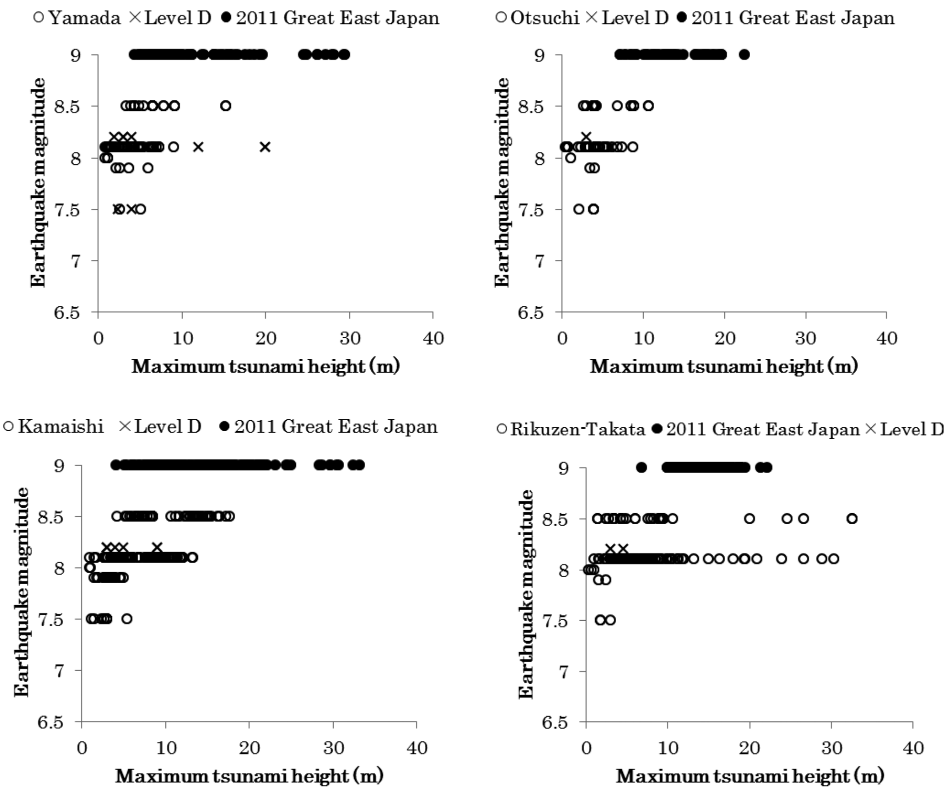

Fig. 4 Plotting of earthquake magnitude and tsunami height in the Sanriku coast of Iwate (Yamada, Otsuchi, Kamaishi and Rikuzen–Takata)

3.3 Sanriku coast of Miyagi

The Sanriku coast of Miyagi region covers areas from Kesennuma to Ishinomaki. The region was affected by the same series of tsunamis as the Sanriku coast of Iwate. Some results are shown in Fig. 5. Unlike the previous region, the *M*7.5 earthquake (in 1856) caused a tsunami of only less than 1 m in Minami–Sanriku and Ishinomaki. In addition, the M8.0 earthquake caused a tsunami greater than 20 m in Kesennuma, which was even greater than the event in 1896 (*M*8.5), which generated a tsunami of less than 15 m.

The 2011 event also caused a large tsunami of approximately 25−35 m in this region. In brief, most areas in this region were comparatively less affected from historical tsunamis, as they experienced less than 15 m tsunamis in all cases prior to the event in 2011. Only in Kesennuma was the local tsunami height comparatively higher, which was similar to the historic records for Ofunato and Rikuzen−Takata in the previously discussed region.

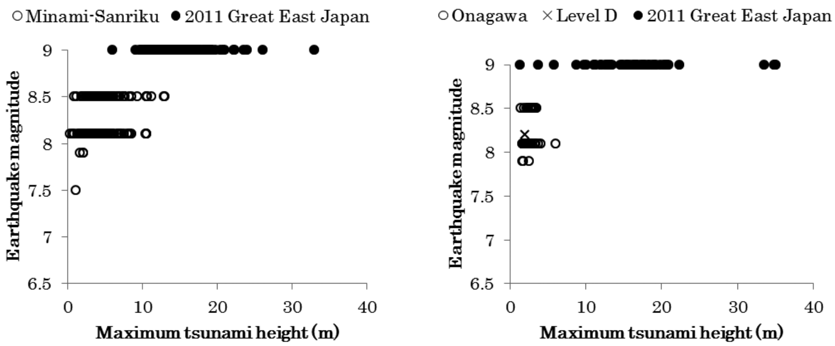

Fig. 5 Plotting of earthquake magnitude and tsunami height in the Sanriku coast of Miyagi (Minami−Sanriku and Onagawa)

3.4 Coastal Plain of Miyagi and Fukushima

This region covers a wide area of coastal plain in the Miyagi prefecture, from Shiogama, passing Sendai, through to Yamamoto and the entire Fukushima prefecture. The results for both areas are shown in Fig. 6. This region has comparatively less historical tsunami trace data, mostly from the 1933 event, and includes some data from tsunamis in 1611, 1793 and 1968. Fukushima was also affected by the Empo Boso tsunami in 1677 (M8.0) from the Kanto region in the south. Unlike the first two regions, this region has historically experienced comparatively small tsunami heights due to its extensive, flat coastal plain area and location far from the source of the tsunamis. The 2011 earthquake generated a maximum tsunami height of roughly 20 m in both areas. Tsunami heights generated by the M8.0 earthquake reached 8 m in Sendai but only 3 m in Fukushima. However, reliability levels in this region might also play an important role, as reliability level D showed maximum heights of 4−8 m for the M8.0 earthquake.

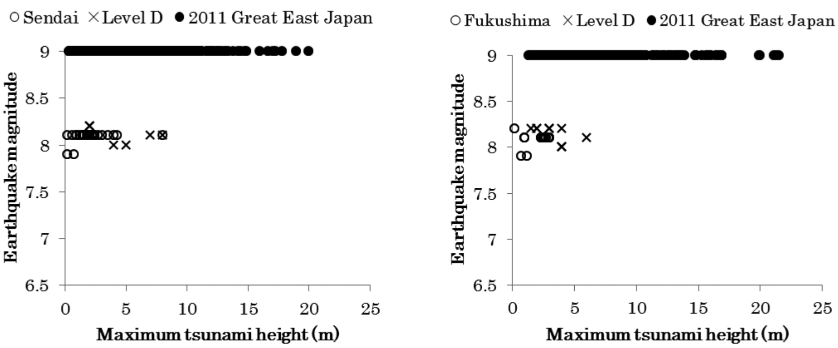

Fig. 6 Plotting of earthquake magnitude and tsunami height in the plain coast of Miyagi prefecture and Fukushima prefecture

4. Relationship between earthquake magnitude and tsunami height

There have been many attempts to estimate tsunami size as a magnitude, intensity and generation mechanism based on an observed or measured tsunami height and to correspond size with earthquake magnitude, such as previous studies by Iida et al. (1967), (Soloview and Go, 1974), Abe (1979 and 1981), Murty and Loomis (1980), Hatori (1986), Shuto (1993), Papadopoulos and Imamura (2001), Choi et al. (2006) and Suppasri et al. (2012b). All of these researchers described the relationship using a logarithmic function of the observed or predicted maximum tsunami height. Therefore, this study will use also the logarithmic function (base 10) to determine a relationship between earthquake magnitude and the maximum tsunami height characteristics of different coastal topography.

Maximum tsunami heights at each historical earthquake magnitude were selected as a representative dataset for each area. Logarithmic values of the selected maximum tsunami height were plotted against the earthquake magnitude. Linear regression analysis was performed to determine the linear relationship using following equation:

$$M = a\log H + b$$

where M is the earthquake moment magnitude, H is the maximum tsunami height and a and b are constant. The parameters are shown in Table 3.

For example, in Yamada in the Sanriku coast (Fig. 7, left), the maximum tsunami heights generated by earthquake magnitudes of 7.5, 7.9, 8.1, 8.5 and 9.0 were 5.1 m, 6.0 m, 9.1 m, 15.24 m and 29.42 m, respectively. The linear regression analysis shown in Fig. 7 (left) yielded values of a = 1.8191, b = 6.3458 and R^2 = 0.9717. In contrast, in Fukushima, located in the coastal plain (Fig. 7, right), recorded maximum tsunami heights of 1.18 m, 3.0 m and 21.52 m from earthquake magnitudes of 7.9, 8.1 and 9.0, respectively for reliability levels A to C. In contrast, maximum tsunami height increases to 4.0 m and 6.0 m for earthquake magnitudes of 7.9 and 8.1, respectively, if reliability level D is also considered. Fig. 7 (right) shows the results of the linear regression analysis with values of a = 0.9002, b = 7.7687 and R^2 = 0.9780.

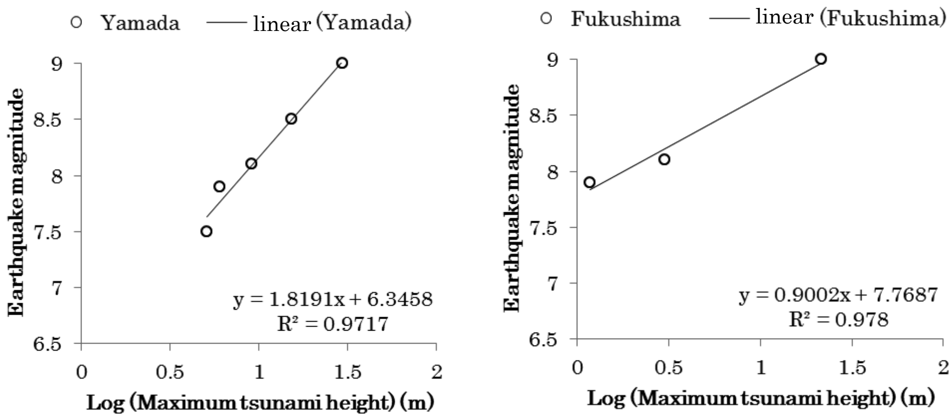

Fig. 7 Relationship between earthquake magnitude with logarithmic value of tsunami height and correlation of the maximum tsunami height at each earthquake magnitude in Yamada and Fukushima

Figure 8 shows the comparison among different tsunami-affected locations, datasets and earthquake type. From the plot of maximum tsunami height and earthquake magnitude shown in Fig. 8, it can be observed that the results can be classified from the tsunami trace database (only cases where $R^2 > 0.85$) into three regions. The first region is the Sanriku coast in Iwate prefecture (Noda, Yamada, Otsuchi and Kamaishi), where even small *M*7.0-7.5 earthquakes are enough to generate tsunamis up to 2-4 m while reaching up to 40 m for the *M*9 earthquake. The second region is the Sanriku coast in Miyagi prefecture (Minami-Sanriku and Onagawa), where small earthquakes generate tsunamis of less than 1 m, but have the potential to generate almost the same tsunami size as the Sanriku coast within the Iwate prefecture for the powerful *M*9 earthquake. The third region is the coastal plain area of Fukushima, where it has had historically less tsunami impacts due to its location and topography. In this region, tsunamis less than 0.5 m are expected from a small earthquake and approximately 20 m for a *M*9 earthquake.

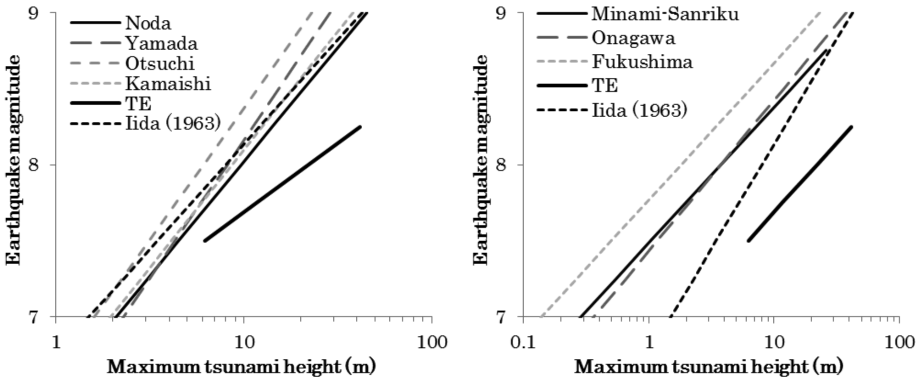

Fig. 8 Relationship between estimated maximum tsunami height and earthquake magnitude for each tsunami-affected location (region)

Previously, Iida (1963) estimated some relationships between earthquake magnitude and tsunami height based on tsunami data in Japan, including the Sanriku coast. These data were used to perform a linear regression analysis to obtain the necessary parameters and the results are shown in Table 3 and Fig. 8. A comparison of the historical tsunamis in Japan proposed by Iida (1963) shows similar results for the Sanriku coast in Iwate prefecture, which was greatly affected by tsunamis in 1896 and 1933. It is surprising that the maximum tsunami height generated by an M9.0 earthquake can also somehow be estimated using the historical data that were limited by an earthquake magnitude of 8.5.

A tsunami earthquake can be defined as an earthquake that generates a larger tsunami height and tsunami magnitude than expected from its seismic waves and can be explained by a long and slow rupture process (Kanamori (1972), Abe (1989), Okal (1993), Geist (1997) and Satake and Tanioka (1999)). Therefore, a tsunami earthquake is also an important issue in this study area because it generates higher tsunamis, such as the 1896 Meiji Sanriku event. Table 4 summarizes tsunami earthquakes worldwide since 1896. Earthquake magnitude range from *M*7.5 to *M*8.3, with corresponding maximum tsunami heights of 5.1-38.2 m. This dataset was also used to analyze and compare with our results. A comparison of the results shows that the maximum tsunami height generated by a tsunami earthquake is greater than any case of non-tsunami earthquake magnitudes.

Table 3 Parameters obtained from the regression analysis of the maximum tsunami height and earthquake magnitude for each area and region

Type	Location	Slope, a	Interception, b	R^2
Northern coast of Iwate	Kuji	1.0986	7.0163	0.8077
	Noda	1.4998	6.5213	0.8763
	Iwaizumi	0.7407	7.5459	0.5791
Sanriku coast of Iwate	Miyako	0.6617	7.5929	0.6594
	Yamada	1.8191	6.3458	0.9717
	Otsuchi	1.7261	6.6468	0.9155
	Kamaishi	1.5502	6.5523	0.8851
Sanriku coast of Miyagi	Minami-Sanriku	0.8936	7.4855	0.9013
	Onagawa	0.9925	7.4325	0.9730
	Ishinomaki	0.7972	7.6178	0.8048
Plain coast of Sendai and Fukushima	Sendai	0.6426	7.8932	0.6745
	Fukushima	0.9002	7.7687	0.9780
Tsunami earthquake	Various	0.9076	6.7804	0.9474
Iida (1963)	Japan	1.5667	7.0781	0.9894

Table 4 Earthquake magnitude and maximum tsunami height of tsunami earthquakes

Year	Name	M_w	Max. tsunami height (m)
1896	Meiji Sanriku	8.3	38.2
1946	Aleutian	8.2	35.0
1960	Peru	7.6	9.0
1963	Kuril Islands	7.8	15.0
1975	Kuril Islands	7.5	5.5
1992	Nicaragua	7.7	10.7
1994	Java	7.7	13.9
1996	Peru	7.5	5.1

5. Conclusions

This study demonstrated the tsunami height distribution for each area along the Tohoku coast based on the historical tsunami trace database and the field survey of the 2011 Great East Japan tsunami. More than 6,000 data points are taken from 14 earthquake events ranging from *M*7.4-9.0 and covering a region from Hokkaido in the north to Kanto in the south. The results show that, in general, the 2011 tsunami was the highest ever recorded but was not the highest in some locations in Iwate prefecture. Reliability level might play a significant role in some areas, where historical tsunami records were comparatively less complete, such as in Sendai and Fukushima.

Further analysis was performed by comparing the maximum tsunami height of each [historic] earthquake magnitude for each area. Linear regression analysis was used to find a relationship between the maximum tsunami height and earthquake magnitude for each region, including tsunami earthquakes. It is clear, and we can confirm, that the maximum tsunami height generated by the same earthquake magnitude is measurably different depending on the location and earthquake type. By comparison, the topography of the northern coast of Iwate and the Sanriku coast in Iwate can cause higher tsunamis, followed by the Sanriku coast of Miyagi and the coastal plain of Miyagi and Fukushima. The results from previous studies show that it is possible to estimate the maximum tsunami height for an *M*9 class earthquake, although this class of earthquake had not been expected to occur in Japan before. Depending on the location, a tsunami earthquake can generate a tsunami 1.5-10 times larger than a non-tsunami earthquake of the same magnitude. The results of the maximum tsunami height versus earthquake magnitude for each region, when compared with other data, were summarized and shown in Table 5.

The results obtained by this study are critical for warning purposes, as we can roughly estimate the probable maximum tsunami height that would be generated by a known earthquake magnitude. In addition, for future research, the same concept can be applied to the west coast of Japan where a powerful earthquake is expected to occur. In 2012, the Central Disaster Mitigation Council, Cabinet Office, government of Japan released the new estimations of tsunami heights generated by an *M*9 earthquake along the Nankai Trough. The findings in this study will be interesting and essential for evaluating predicted tsunami heights using the available historical tsunami database, as it has been successfully analyzed and confirmed by this study.

Table 5 Estimated maximum tsunami height for each earthquake magnitude for each region

Earthquake magnitude	Sanriku (Iwate)	Sanriku (Miyagi)	Sendai and Fukushima	Tsunami earthquake
7.0	2	0.5	0.2	N/A
7.5	5	1	0.5	7
8.0	10	4	2	15
8.25	12	8	4	40
8.5	20	16	8	N/A
8.75	25	24	12	N/A
9.0	40	32	25	N/A

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