The Influence of Man-made Structures and Land-use on the Behavior of Tsunami from the 2011 Great East Japan Earthquake: Some Examples from the Pacific Coast of Tohoku and Hokkaido

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Abstract
A drastic change in the behavior of the 2011 Tohoku earthquake tsunami at specific sites or on a local scale was caused by changes in coastal setting, land uses for fisheries, large-scale river course changes, and coastal construction works such as super embankments, jetty ports, dredged ports and types of breakwater seawalls. Such phenomena could be identified along not only the coast of Tohoku close to the epicenter, but also that of Hokkaido, relatively far from there. This report presents some remarkable examples of the influence of man-made structures and land-use on the site-specific to local tsunami behaviors along the Pacific coast of Tohoku and Hokkaido from the geomorphological view, and must provide the information for the adequate mitigation to future tsunami disasters and evacuation from them.

Key words: 2011 Tohoku earthquake tsunami, coastal construction, geomorphological setting, land-use change, site-specific tsunami behavior

1. Introduction
On March 11, 2011, a magnitude 9.0 earthquake occurred off the Pacific coast of northeastern Japan (Tohoku) and generated a tsunami that struck along 2,000 km of the Pacific coast of Japan. The tsunami reached the Pacific coast of Hokkaido, the northernmost island of Japan, about one hour after the earthquake. According to the data of the 2011 Tohoku Earthquake Joint Survey Group (2011), the tsunami rose to a height of more than 30 m in valleys along the Tohoku coast close to the epicenter, and reached a height of approximately 20 m to flood more than 5 km inland along the Sendai Plain. Even in Hokkaido, 300-600 km north from the epicenter, the tsunami inundated most parts of the Pacific coast to heights of 2-4 m, but some spots to 5.5-6.7 m (Fig. 1).

From the viewpoint of disaster mitigation and evacuation it should be noted that the run-up behaviors of the 2011 Tohoku tsunami were probably sensitively influenced by wave breaking and diffraction associated with not only physiographic coastal settings, but also coastal land-use and/or location/arrangement of various coastal construction works, as already pointed by Mori et al. (2011, 2012). It seems, however, that there have been insufficient site-specific or local observations and interpretations of such tsunami behaviors, especially from a geomorphological point of view. Therefore, this report aims to introduce some remarkable examples of the tsunami run-up behavior along the Pacific coast of Tohoku and Hokkaido in terms of geomorphology, and to propose its consideration as important to the planning for mitigation and evacuation in future tsunami disasters.

2. Outline of Study Area and Methods
This report presents the tsunami run-up behaviors observed in two areas (the lowermost reaches of the Kitakami River and the town of Taro) on the Pacific coast of Tohoku and four areas (Asahihama, Tokachi Ohtsu, the town of Erimo, and Cape Erimo) on that of Hokkaido. Their localities are shown in Fig. 1.

In the Tohoku region, we interpreted the tsunami run-up behavior associated with large-scale landform transformation (man-made river channels) and a super embankment. For this purpose, we read not only topographic maps, but also referred to compiled data (e.g., Haraguchi & Iwamatsu, 2012) on the inundation area and run-up height of the tsunami in the Tohoku region.

In the Hokkaido region, we focused on comparatively site-specific tsunami run-up behaviors related to changes in the coastal setting, land use, and coastal structures such as jetty harbors, reclaimed land and tidal seawalls, based on topographic map readings and field observations.
Fieldwork was conducted along the Pacific coast of Hokkaido, focusing on the Hidaka and Tokachi coasts from March 17 to 19, one week after the earthquake, and April 2 to 4. Through our fieldwork, we carefully observed tsunami traces with special reference to coastal construction works. Simultaneously, inundation height and/or run-up height were measured from the extent of debris, reworked beach sediment and water marks by using laser range finders. Measured heights were corrected for tidal elevation for a comparative investigation, although the relative (real time) height of the tsunami inundation and run-up would be significant to the people living in the individual areas or sites.

3. Observations and Descriptions

3.1 The New Kitakami River and the tragedy of Okawa elementary school

Along the lowermost reaches of the Kitakami River with the fourth largest drainage basin in Japan, a tragedy happened at an elementary school. Seventy-four of 108 pupils and ten of 11 teachers at the school became victims of the tsunami. The pupils were waiting on the school grounds, while the teachers were discussing to where they should evacuate. About 50 minutes after the earthquake, the tsunami attacked the pupils and teachers, although the school was located at approximately 5 km inland from the coast (Fig. 2). They seem not to have considered their dangerous geomorphological situation, as described below, because of the relatively long distance from the coast.

The main reason the tsunami violently intruded so far inland, more than 15 km in this valley, can be attributed to the geomorphological setting tied to landform development and the man-made river channel structure. Through the Holocene transgression, this whole valley had been inundated, developing a ria-inlet or strait (Ito, 1999). Due to this, the valley floor, starting from the tidal flat, consists of successional wetlands, the elevation of which is only 0-2 m above sea level up to the approximately 15 km upstream from the present river mouth. The man-made New Kitakami River channel was constructed, along with a riverside dike 5 m high from 1911 to 1934, using such characteristic lowland landforms. Here we should note that the New Kitakami River channel with a width >500 m led to the violent, rapid run-up of the 2011 tsunami far (approx. 14 km) into the valley.

The residents, particularly the teachers, should have known about such a dangerous geomorphological setting and recent artificial changes to the river channel in order to evacuate safely or mitigate damage from the tsunami disaster. It must be stressed that understanding the development of local-scale landforms and land-use changes like the New Kitakami River channel is a key issue for disaster prevention.
3.2 The super embankment of Taro town

Taro is a small town situated along a narrow lowland in a bay, where a world famous “super embankment” had been constructed. Residents of the town of Taro had frequently suffered from tsunami attacks, such as those of 1896 Meiji-Sanriku and 1933 Showa-Sanriku earthquakes, and therefore began to construct a huge dike, the “super embankment,” after the 1933 tsunami on their own initiative. What role did the super embankment play in the 2011 tsunami? What difference in tsunami inundation and run-up in this area was there between the super embankment and the breakwater seawall constructed later from the 1960s to 1970s?

Figure 3 shows the embankment arrangement and the inundation and run-up heights of the 2011 tsunami at some localities in and around the town. As shown in Fig. 3, the tsunami inundation and run-up heights were highly variable at individual sites within such a narrow area. We can see that a tsunami with a height of 30 m or higher ran up into the small valleys. Even in the area behind the breakwater seawall constructed from the 1960s to 1970s, which was severely destroyed by the 2011 tsunami, the tsunami maintained a run-up height of nearly 20 m. In contrast to these areas, a tsunami with a relatively lower inundation height of 10 m or even less could be found in the residential area behind the super embankment. Because the height of the super embankment is 10 m above sea level, the tsunami appears not to have violently attacked, but to have just completely inundated the protected hinterland. Therefore there were no victims, although people evacuated to the schools located in the small valleys at about 10 m above sea level.

The super embankment, which has a slope of 45 degrees on both sides of the cross section, was not destroyed anywhere by the 2011 tsunami. The tsunami appears to have smoothly overflowed the super embankment due to its structure and form with the 45 degree angle. On the other hand, the damaged newer breakwater seawall surrounding the fisheries port should have worked to weaken the tsunami energy, although it appears to have been comparatively easily constructed with a thin, vertical structure. Here we can draw attention to the aerial arrangement of seawalls, where the super embankment seems to have more or less mitigated the 2011 tsunami disaster in Taro, although the town was severely damaged.

3.3 The fisheries port and coastal changes at Asahihama

The 2011 tsunami behaved very variably from one site to another in and around the port, depending on coastal conditions, as indicated in Figs. 4B, C and D. In this section, we first explain the coastal setting at Asahihama in order to promote understanding of the variability of tsunami behavior on the coast. Next, we document the features of tsunami inundation and run-up in the following three areas: the fisheries’ port and the beaches northeast and southwest from the port.
3.3.1 Coastal setting

At Asahihama in Hokkaido, the fisheries jetty port with reclaimed land is protected by breakwater seawalls of 5 to 7 m high (Fig. 4). Such engineering works have been constructed since 1973 to the present. Due to the construction of the jetty port, the supply of drift sand/gravel associated with longshore currents to the beach has been completely stopped on the north side of the port. In contrast, this jetty port has worked to trap drift sand/gravel on the beach on the south side of the port. As a result, coastal erosion and accretion on both sides of the port has occurred notably since then (Fig. 4B), and continues at present.

In fact, the beach profile in the erosional reach has been changed to present a narrower and steeper backshore zone. Furthermore, the backshore zone is already lacking at some sites, so that the run-up of waters from breakers has begun to reach the sea cliff directly. Therefore, in the severely eroded reaches, sea cliffs with a height of ~10 m have been protected by the seawall, which is up to 5 m in height, and has a slope with an angle of 45 degrees, during the last ten years (Fig. 4C).

On the other hand, drift sand/gravel in the accretion reaches has accumulated up to a height of 4.5-5 m, and has newly formed a beach foreshore and backshore in front of an upland, which has a sea cliff of ~5 m (Fig. 4B). The height of the new beach has nearly reached that of the former sea cliff, meaning that the sea and upland have been connected with a gentle slope.

3.3.2 Fisheries port

The tsunami inundation height indicated by watermarks on the walls of storage houses was 3.4 m on reclaimed land within the port protected by the breakwater seawall (a height of ~5 m) (Fig. 4B). Namely, the tsunami had not exceeded the breakwater seawall of the port. As a result, the fluctuation of the tsunami was recorded by several levels of watermarks, indicating a repeated tsunami. This means that the inundation height in the port appears to approximate the tsunami wave height along the coast, like those measured by the tide gauge.

Just outside the port, however, a tsunami with a run-up height of 5.8 m flowed over the breakwater seawall at 5.0 m and into the reclaimed area (Fig. 4B). This place is a specific area behind the jetty port, where accretion of beach drift due to circulating currents is occurring. The foreshore has a large slope gradient corresponding to beach gravel of cobble to boulders, and therefore favored a higher run-up.

3.3.3 Beach northeast from the port

The beach northeast from the port is characterized by progressive coastal erosion, which has occurred since 1973 (Fig. 4B). Our observation of this beach shows that the sudden change in tsunami run-up height coincides with the engineered stretch. In the stretch of non-engineered beach where the foreshore and backshore had been maintained sufficiently in front of the sea cliff of
5 m height, the tsunami run-up height was 3-4 m and did not extend inland. On the other hand, the tsunami ran up the sea-cliff protection, which had an angle of 45 degrees, and reached a height of 8-9 m above sea level (Figs. 4C and D). This run-up height was about 2.5 times higher than that of the non-engineered reach. This fact strongly suggests that the tsunami run-up was site-specifically enhanced by the disappearance or reduction of the backshore. Therefore, it can be considered that such site-specific amplification of the tsunami run-up was evidently related to changes in the coastal condition. Particularly in this case, we should stress that the tsunami easily and smoothly ran up a side-slope of 45 degrees, which was there for sea cliff protection, like the tsunami did at the super embankment in Taro, Tohoku.

3.3.4 Beach southwest from the port

The beach southwest from the port has accreted seaward since 1973 (Fig. 4B). Accreted beach sediment has already reached the top of the breakwater seawall of the port (~5.0 m high). This means that the tsunami could potentially run up such a new beach easily and flow into the port. The actual tsunami ran up to a height of 4.5 m, i.e., an invasion of the port by the tsunami was barely missed.

3.4 Tokachi Ohtsu

The tsunami inundation and run-up around the Tokachi Ohtsu fisherie’s port differed between the dredged port and a roadside seawall (Figs. 5A and B). The details are described below.

The dredged port had been constructed by excavating a wetland which was geomorphologically identified as an abandoned river course and marsh behind a beach ridge. The inundation height of the tsunami in the port was 4 m based on a watermark on the wall of a structure. The pattern of the tsunami inundation (Fig. 5B) clearly indicates that the tsunami intruded inland according to the original micro-landform of the dredged port. Namely, the tsunami run-up in this area appears to have been strongly controlled by the former micro-geomorphic conditions. One of the issues to be considered is that the evacuation...
route, which actually suffered from tsunami inundation, bypass the periphery of the dredged port.

On the other hand, the run-up height of the tsunami at the roadside seawall stretching southwestward from the port and village was 6.5 m, which was significantly higher than that of 3.5-4 m within the port or on the beach. Such an enhanced tsunami run-up was probably due to bank protection along the roadside against waves, as shown in Figs. 5C and D. This means that coastal construction changed the tsunami run-up site specifically. In terms of evacuation, it should be carefully considered that the road along the roadside seawall was inundated by the tsunami.

3.5 Erimo town, Shin-hama

The tsunami run-up height around the port of the town of Erimo varied from the site to site (Fig. 6), probably as a result of the influence of the jetty port, the tide seawall, and the arrangement of tetrapods. The inundation height and run-up height within the reclaimed lowland of the port marked 2.8-3.7 m (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011; Okazaki & Tsunami Survey Team of the Geological Survey of Hokkaido, 2011), and 3.5-3.8 m (Fig. 6B), respectively. In comparison with this reclaimed land, a higher run-up height reaching 5.5-6 m was identified outside the port to the south (Fig. 6B), due to the direction of tsunami propagation. Houses protected by a 3.5 m tidal seawall were inundated (Fig. 6B). In addition, the tsunami ran up the small valley in this area to some degree, and then destroyed just one house and a small part of the seawall (Figs. 6B and C) by its drawback. Additionally, the higher run-up of the tsunami seems to correspond to a break between tetrapod mounds.

In summary, such an observation indicates that the tsunami inundation and run-up changed in accordance with coastal construction works. Namely, the jetty system structure of the port probably worked to trap and amplify the tsunami to a very small extent. Simultaneously, the arrangement of tetrapod mounds likely influenced the tsunami run-up at the site scale.

3.6 Cape Erimo

Another characteristic tsunami run-up was recorded on the coast near the Cape Erimo Port as shown in Fig. 7. A part of this beach is used as a sea tang (seaweed) drying
Due to this land use, no engineering works had been constructed there, apart from the jetty port (Fig. 7).

The tsunami ran up over the whole seaweed drying ground area that can be identified as the natural foreshore and backshore with gentle slopes. The run-up height was recorded as ~6.5 m on the southern part of the coast, and decreased toward the port to the north (Fig. 7B); in fact, it was 4 m in the port. Such a pattern of the tsunami run-up height and the arrangement of the port suggest a possibility that the jetty seawall of the port trapped the tsunami, which propagated from the southeast, and then caused a site-specific amplification of tsunami run-up south of the port. Therefore, when thinking about

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Fig. 6  Tsunami inundation and run-up influenced by coastal construction works around Erimo Town Port, Shin-hama (see Fig. 1 for location). (A) Topographic map. Box shows location of (B). (B) Inundation and run-up heights in meters. The arrow shows the direction of tsunami inundation. “p” in (B) indicates the shot point for Photo (C). Google Earth image used for the base map of (B).

Fig. 7  Tsunami inundation and run-up height around Cape Erimo Port (see Fig. 1 for location). (A) Topographic map. Box shows the location of (B). (B) Inundation and run-up heights in meters. Arrows show direction of tsunami run-up onto the sea tang drying ground. Google Earth image used for the base map.
tsunami run-ups we should assume that the coastal setting together with the specific land use for fisheries can cause a difference in the tsunami run-up.

4. Remarks

It is well known that many factors affect local tsunami behavior. The key issue in this report is to present some examples concerning the violent behavior and drastic changes in the 2011 Tohoku earthquake tsunami associated with human modification of the coastal setting in Tohoku and Hokkaido.

As pointed out from the case of the man-made channel of the New Kitakami River in Tohoku (Fig. 2), an understanding of the coastal setting tied with the development of local-scale landforms and land-use change is critical for disaster prevention. Moreover, the case of the town of Taro in Tohoku (Fig. 3) suggests that the relationship between the 2011 tsunami on a local or site-specific scale and the arrangement and structure of embankments must be analyzed for adequate evacuation and mitigation of future tsunamis.

On the Pacific coast of Hokkaido, far from the epicenter, the inundation and run-up height of the 2011 tsunami was generally 2-4 meters (Fig. 1). As already described in Sections 3.3-3.6, however, sudden higher values of tsunami inundation and run-up height ranging from 6 to 9 m could be identified at some specific sites (Figs. 4, 5, 6 and 7), where coastal engineering work had been done. Therefore, the effectiveness of various engineered coastal structures, including fisheries ports, must be carefully discussed hereafter based on site-specific observations and analysis of tsunami behavior. Without such information, it is difficult to grasp the restricted inundation and run-up of a tsunami in relation to fisheries ports’ structures, land use, engineering works against coastal erosion and so on. The direct influence of such artificial roughness on a tsunami should be noted and considered to avoid dangerous situations in evacuation and mitigation.

We have to imagine the tsunami inundation and run-up as described above, even when a moderate tsunami occurs. This is because people near the Pacific coast of Hokkaido only narrowly escaped severe damage from the 2011 Tohoku tsunami, considering the site-specific irregular height of tsunami inundation and run-up related to human coastal modification.

References


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(Received 17 February 2014, Accepted 4 April 2014)