Numerical simulation of the tsunami generated by the 2007 Noto Hanto Earthquake and implications for unusual tidal surges observed in Toyama Bay

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We conducted a numerical analysis of the tsunami generated by the 2007 Noto Hanto Earthquake ($M_{\rm j} = 6.9$) that occurred on 25 March 2007 near the Noto Peninsula on the northwest coast of Honshu Island, Japan. Our numerical simulation reproduced well the behaviors of the tsunami as recorded at the Wajima tidal observatory and showed that the computed tsunami arrived in Toyama Bay more than 1 h after the earthquake. However, a crew of a small boat in the bay felt the shock and, despite calm weather conditions, their boat capsized just 3 min after the earthquake. Although abnormal tidal surges were recorded at several locations around Toyama Bay, the timing of these is inconsistent with the surges being a direct result of the tsunami generated at the source area of the earthquake. We used "backward wave propagation analysis" to estimate the likely source area of the abnormal tidal surges in the bay and carried out the a simulation of landslide-induced tsunami. Our conclusion is that these abnormal tidal surges were likely caused by a submarine landslide on the steep sea floor on the western side of Toyama Bay.
Key words: The 2007 Noto Hanto Earthquake, tsunami, Toyama Bay, abnormal wave.

1. Introduction

At 9:42 a.m. (Japan Standard Time) on 25 March 2007, an earthquake occurred near the Noto Peninsula (37.19°, 136.55°), Japan. The Japan Meteorological Agency (JMA) estimated the earthquake was of magnitude 6.9. A tsunami was generated by the earthquake and arrived at Wajima (Fig. 1(a)) at about 10:04 a.m. The maximum height of the wave was 8 cm (Fig. 1(b)).

Sharp tidal surges were also recorded at three tidal observatories (Fig. 1(a)) within Toyama bay just 5 min after the earthquake (Fig. 2). The short interval between the earthquake and the tidal surge suggests, however, that the surge may not have been a tsunami generated directly by fault movement at the seismic source off the Noto Peninsula. The tsunami from the earthquake would have required at least several tens of minutes to an hour to propagate around the Noto Peninsula over a distance of more than 200 km to reach Toyama Bay (Fig. 1(a)). However, it is noteworthy that a small boat capsized in Toyama Bay immediately after the earthquake (Prime Minister of Japan and His Cabinet, 2007). According to the boat crew, the weather was fine with no strong waves or swell before the boat suddenly capsized shortly after the crew heard a radio report of the earthquake at around 9:45 a.m. Therefore, it is difficult to attribute the boat's capsize to the tsunami generated by fault movement at the seismic source. On the basis of these observations, we speculate that unusual phenomena may have occurred locally in Toyama Bay immediately following the earthquake. In the study reported here, we undertook a numerical analysis of the tsunami generated by the 2007 Noto Hanto Earthquake with the aim of modeling the generation and propagation of the tsunami and estimating its arrival time in Toyama Bay. We also investigated the possible cause of the unusual tidal surge in Toyama Bay by using back-propagation analysis to determine the source of the observed wave.

2. Numerical Calculation of the Tsunami Generated by the 2007 Noto Hanto Earthquake

2.1 Method for the numerical calculation

We calculated a propagation model of the tsunami using the fault model proposed by the Geographical Survey Institute (GSI) (2007). This is a fault that is 21.2 km long and 13.9 km wide. The upper depth of the fault is 1.2 km, and it has a strike of 55°, a dip at 63°, with a slip angle of 137°, and a dislocation of 1.65 m. The water-level distribution immediately after movement on the fault plane (Fig. 1(a)) was calculated using fault parameters from Mansinha and Smylie (1971). We applied a model for tsunami propagation and inundation that uses non-linear shallow-water equations, including a bottom-friction term (Imamura, 1995). This model uses a finite-difference method, which is known as the staggered leap-frog method. We used bathymetric data with a 150- and 450-m grid-cell size. The calculation time was 3 h and the time-step interval was 0.1 s.

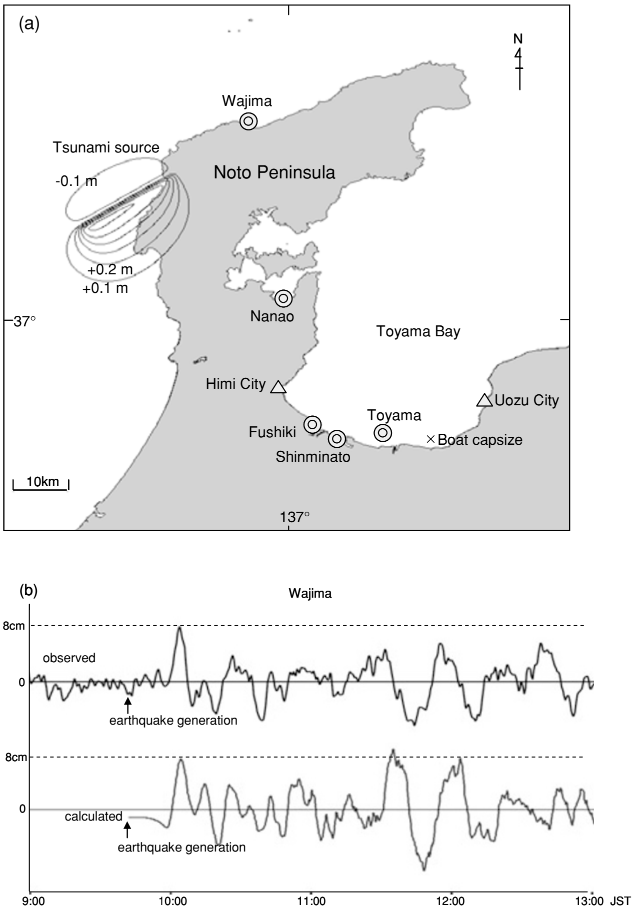

Fig. 1. (a) Map of the study area showing the tsunami source area, locations of tidal observatories (gray circles), and cities from which weather records were obtained (gray triangles). The contours at tsunami source show the vertical disturbance of water by the 2007 Noto Hanto Earthquake (0.1-m interval). (b) Comparison of computed and observed tidal data at Wajima. Observed tidal data was provided by the Port and Airport Research Institute.

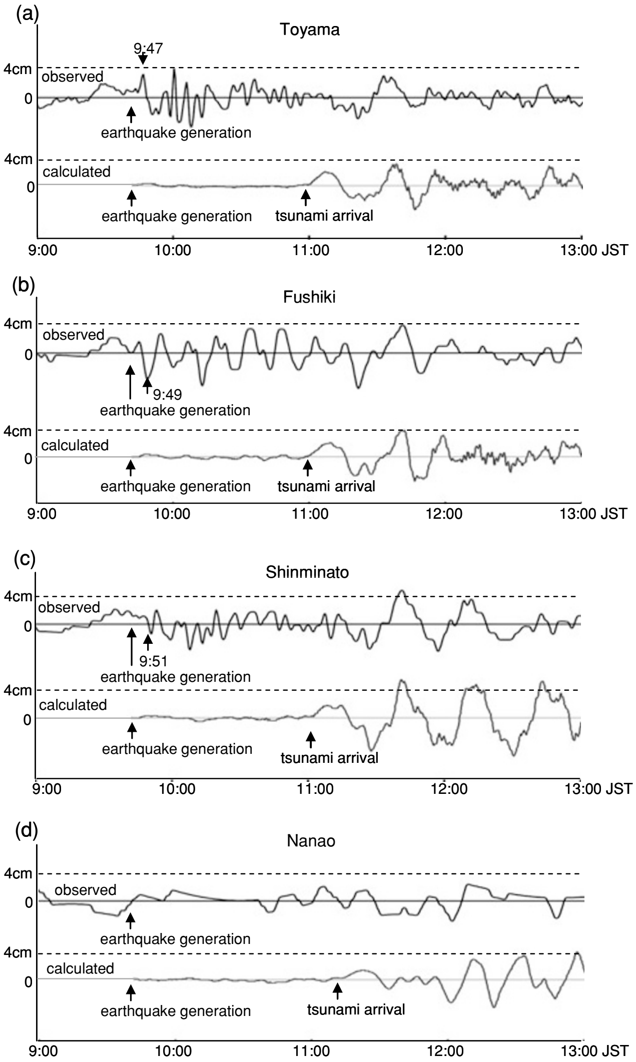

Fig. 2. Time-series variations of observed and calculated tidal levels at (a) Toyama, (b) Fushiki, (c) Shinminato, and (d) Nanao tidal observatories. Observed tidal data were provided by the Port and Airport Research Institute.

2.2 Results and discussion

According to the record at the Wajima tidal observatory on the northern coast of the Noto Peninsula, a tsunami generated by the earthquake arrived at Wajima at about 10:04 a.m. Its maximum wave height was 8 cm (Fig. 1(b)). The modeled arrival time of the first tsunami was approximately 10:03 a.m. and its wave height was estimated as 7 cm (Fig. 1(b)). These modeled results are consistent with the observations.

Tidal surges were also recorded at observatories in Toyama Bay (Fig. 2). At the Toyama observatory, a sudden sea level rise started at 9:45 a.m. and peaked at 9:47 a.m. (Fig. 2(a)). At the Fushiki observatory, the sea level started to drop suddenly at 9:46 a.m., reaching its lowest level at 9:49 a.m. (Fig. 2(b)). Similarly, at the Shinminato observatory, a sudden drop of sea level started at 9:49 a.m., reaching its minimum level at 9:51 a.m. (Fig. 2(c)). No tidal change was recorded at the Nanao observatory immediately after the earthquake (Fig. 2(d)).

Figure 3 shows wave front lines of our modeled tsunami propagation at every 10 min after the earthquake generation. The modeled tsunami arrived at Toyama Bay 75 min (10:57 a.m.) after the earthquake generation (Fig. 3). This result strongly suggests that the tidal surges recorded in Toyama Bay during the hour immediately following the earthquake cannot be explained by the tsunami generated at the seismic source.

3. Description of the Capsize of the Boat

A small boat (6.3 m long according to the Asahi newspaper, 2007) capsized near the southern shore of Toyama Bay shortly after the earthquake (Fig. 1(a)). According to the boat crew, who informed the Japan Coast Guard, the boat started to vibrate and was suddenly uplifted while at anchor and facing west. Two or three minutes later, at about 9:45 a.m., the boat crew heard the radio announcement about the earthquake, and the boat was again strongly uplifted. Shortly after the second uplift, the boat overturned toward the port side.

No unnatural waves, such as a bow wave or ship's wake, were observed by the boat crew both before and after the capsize. Moreover, weather conditions on southern Toyama Bay at that time were calm, with the wind veloc-

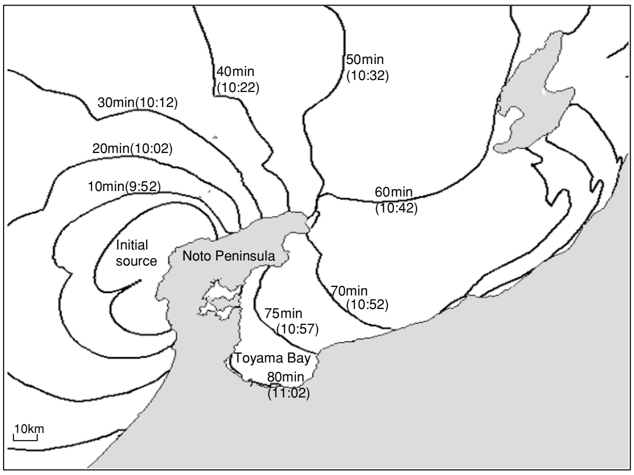

Fig. 3. The map showing wave fronts of the calculated tsunami wave (10-min interval), which suggests that the earthquake-induced tsunami arrived at Toyama bay 70–80 min after generation.

ity around 2 m s^{-1} (JMA, 2007). According to weather data recorded at 10-min intervals at Uozu and Himi on the shore of Toyama Bay (Fig. 1(a)), there was a westerly wind with a wind velocity of 1 to 2 m s^{-1} at that time (JMA, 2007). Therefore, neither waves from boat activity nor wind-generated waves can explain the capsizing of the boat.

According to the crew, the boat was overturned toward the port side while anchored with the bow facing west. Therefore, it is possible to speculate that an extraordinary wave (or waves) traveling from north to south (landward) might have struck the starboard side of the boat and caused it to capsize.

4. Possible Cause of the Unusual Tidal Surges in Toyama Bay

Our numerical analysis revealed that the arrival time of the tsunami at Toyama Bay was about 11:00 a.m. Therefore, it is very difficult to explain how the capsize of the boat might have been induced by the tsunami generated by fault movement at the seismic source off Noto Peninsula. The seaquake may have been generated by the 2007 Noto Hanto Earthquake. Seaquakes are sometimes generated by large earthquakes and are a major cause of boats and ships capsizing immediately following an earthquake (e.g., Okamoto and Sakuta, 1995). Considering the arrival time of the seaquake, the first vibration felt by the crew immediately after the earthquake might have been caused by the seaquake, although the boat did not capsize as a result of this first vibration. On the other hand, unusual tidal surges were observed at some tidal observatories (Toyama, Fushiki, and Shinminato) in Toyama Bay. The onset of the tidal surge was almost consistent with the time that the boat capsized. Therefore, we prefer the hypothesis that not the seaquake but the tidal surge in Toyama Bay caused the boat to capsize.

If so, what caused the tidal surge, which was observed only within Toyama Bay? Because of the steep bathymetry in Toyama Bay and the surrounding area (Fig. 4(a)), submarine landslides are common. They have been attributed to floods or failures on fan delta frontal slopes as well as to seismic activity (Nakajima *et al.*, 1998). Based on analyses of drill cores from the Toyama deep-sea channel system, turbidites have been regularly deposited there at intervals of approximately 70 years (Nakajima *et al.*, 1998; Nakajima, 2006). Therefore, it is possible that a submarine landslide was triggered near the southern margin of Toyama Bay by the 2007 Noto Hanto Earthquake. Interestingly, a fisherman who was on a boat offshore of Himi city (Fig. 1(a)), mentioned that the seawater became muddy after he heard a large sound immediately following the earthquake (from a survey by the Fisheries Agency, personal communication), probably due to the suspension of the sea bottom sediments. Based on these observations, we suggest that the likely explanation is that a local submarine landslide, triggered by the 2007 Noto Hanto Earthquake, caused the tidal surge in Toyama Bay.

Because the tidal surge was observed at several observatories in Toyama Bay, we can estimate the source area of the submarine landslide using a back-propagation method.

5. Estimation of the Possible Source of the Submarine Landslide

The onset of the sharp tidal surge at Toyama observatory arrived 3 min after the earthquake (9:45 a.m.), and the peak level arrived 5 min after the earthquake (9:47 a.m.). If we assume that the tidal surge was generated within Toyama Bay immediately after the earthquake (9:42 a.m.), we can consider a virtual source of the wave at the Toyama observatory and back-calculate the propagation time of the wave from the observatory. Figure 4(a) shows the loci of points from which the onset and the peak of the wave that arrived at the Toyama observatory may have come. Similarly, we back calculated propagation times for the onset of the sharp drop of tidal level observed at the Fushiki observatory (4 min after the earthquake, 9:46 a.m.) and the lowest level (7 min after the earthquake, 9:49 a.m.). In the case of the Shinminato observatory, the onset of the sharp drop in tidal level occurred at 5.5 min after the earthquake (9:46 a.m.) and the lowest level at 8 min after the earthquake (9:50 a.m.). The loci of the possible origin of the onset and peak of this wave are also shown on Fig. 4(a). To reproduce the peak of the tidal surge at the Toyama, Fushiki and Shinminato observatories, the wave source must lie between the lines defining the 3- and 5-min propagation times for Toyama, between those defining the 4- and 7-min propagation times for Fushiki and also between those defining the 5.5- and 8-min propagation times for Shinminato.

The proper analysis of wave generation and propagation due to a possible submarine landslide requires a numerical calculation using a landslide-generated wave model (e.g. Imamura and Imteaz, 1995; Matsui *et al.*, 2002). However, the precise scale of the initial movement of sediments is very important in the calculation of landslide-generated waves. Because we do not have any information about a possible submarine landslide in Toyama Bay at the present time, we cannot model wave generation and propagation using such a model. A depth-sounding survey and core-drilling program are required to determine whether there was a landslide, where it occurred, and its scale. Thus, in this study, we did not use the landslide-generated wave

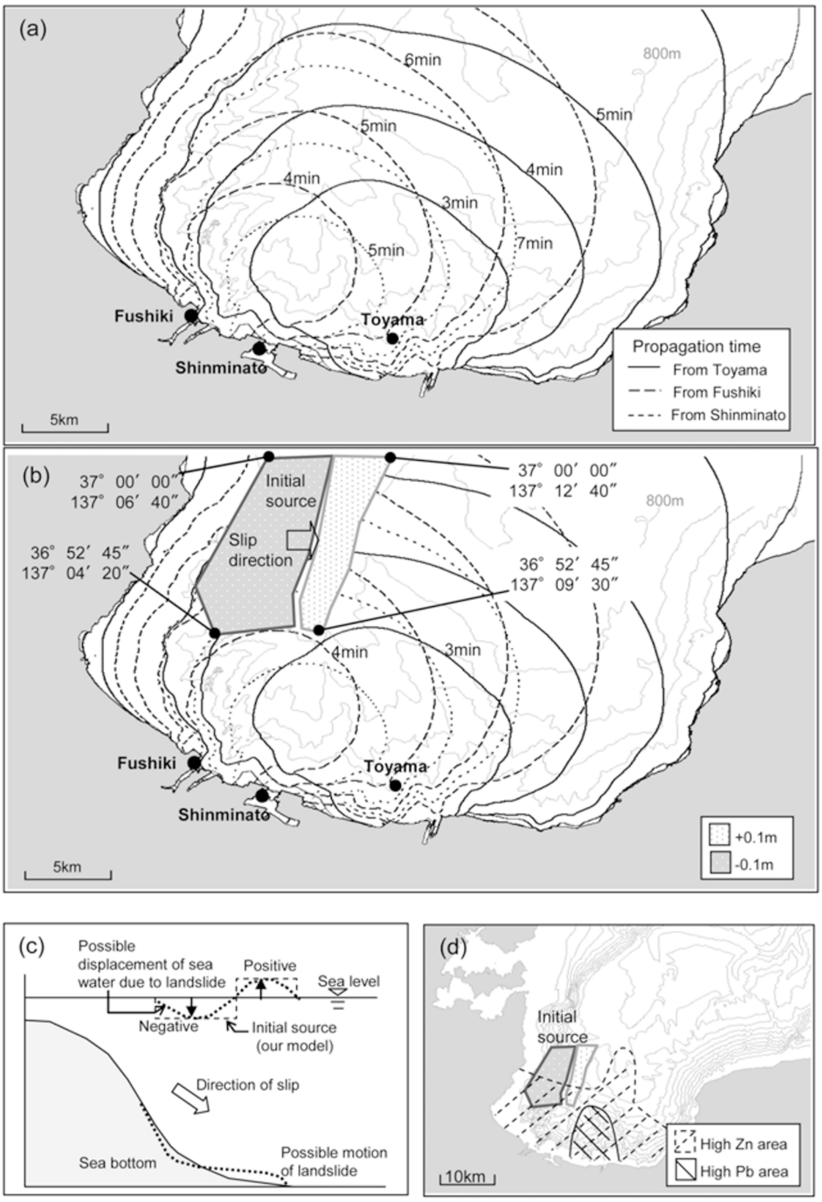

Fig. 4. (a) Map showing the loci of the possible origins of the onset and peak of the tidal surges recorded at Toyama, Shinminato and Fushiki observatories, which are estimated by backward wave propagation analysis. (b) Proposed source area of the tidal surge, flow direction of the landslide, and vertical displacement. (c) Cross section showing the ideal geometry of the landslide, and the wave it generated, and our model. (d) Map showing the place that metals such as Pb and Zn are exceptionally high (based on Imai *et al.*, 1997).

model. As a preliminary interpretation, taking into account the sea-floor physiography of the bay, we considered a virtual vertical sea displacement either along the slope or at the bottom of a valley in Toyama Bay (Fig. 4(b)) as possible source areas of the submarine landslide. This in turn indicates that we did not consider the sea floor displacement in this calculation but just set the vertical sea displacement at the possible landslide area. These locations and sizes of the area were set to satisfy the range of arrival times that we estimated from back propagation times.

To imitate the motion of the sea water during the landslide flow process, we assumed negative vertical displacement when we set the wave source on the slope (Fig. 4(c)). On the other hand, we assumed positive vertical sea displacement when we set the wave source on the flat floor. We found that the onsets of the tidal surge at Toyama and Fushiki can be successfully explained (Fig. 5) only when we set an initial source of the wave on the slope of the western part of the Toyama Bay (Fig. 4(b)). Therefore, the landslide was likely generated in the western part of the Toyama Bay in the area offshore of Fushiki.

It is important to note that the onset of the tidal surge observed at the Toyama observatory was a wave of positive amplitude, whereas negative amplitudes were observed at the Fushiki and Shinminato observatories (Fig. 2). This difference is probably related to the flow direction of the submarine landslide. For example, if the submarine landslide ran along the channel from south to north in the bay, the first tidal level change would be negative at all observatories because they are located in the upper channel south of the source area of the landslide (Fig. 4(c)). Conversely, if we assume that the initial movement of the landslide was

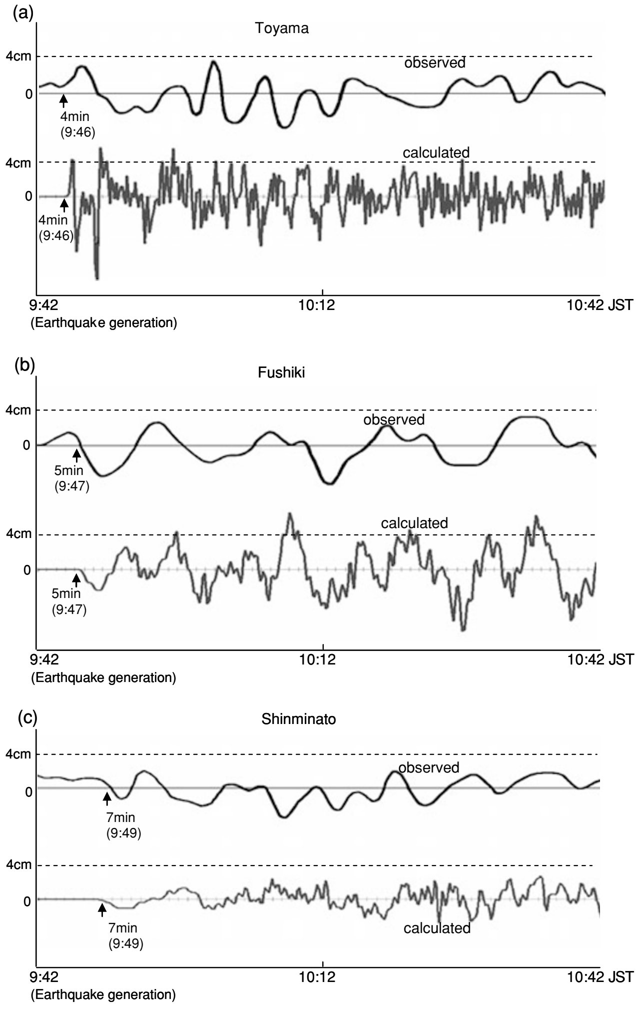

Fig. 5. Comparison of time-series variations of the observed and calculated tidal levels at the Toyama, Fushiki, and Shinminato tidal observatories. The calculations are obtained by the simulation of submarine landslide-induced tsunami, shown in Fig. 4. Although the calculated tidal levels could be same as the observed ones overall, the former include the shortened wave period component movement.

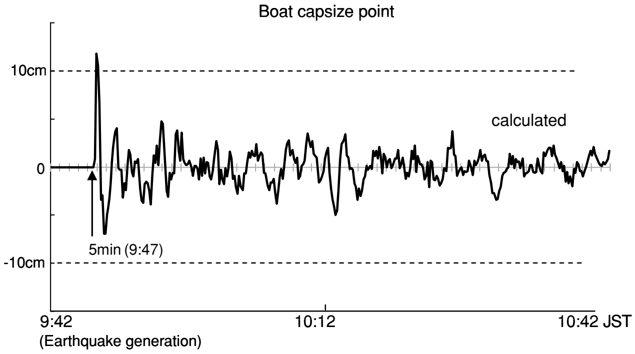

Fig. 6. Time-series variation of tidal level calculated at the location where the boat capsized.

eastward at the source area, which is consistent with the slope direction, a positive wave would propagate toward the Toyama observatory, and a negative wave would propagate toward the Fushiki observatory. This suggests that the landslide might have initially flowed down the eastward dipping slope (Fig. 4(b)).

We also tested several initial displacements of sediment to reproduce the height of the initial wave at each observatory. We found that a sharp rise at the Toyama observatory (Fig. 5(a)) and drops at Fushiki and Shinminato observatories (Fig. 5(b) and (c)) are well explained if we set the initial displacements at $+0.1$ m in the eastern part of the source area and -0.1 m in the western part (Fig. 4(b)), although the wave periods at each observatory are very different from the observed data. We also used this model to calculate the amplitude of the tidal surge at the location where the small boat capsized. Our calculations show that the tidal level would have drastically increased by more than 10 cm at this location at about 9:47 a.m. (Fig. 6), which is consistent with the time at which the boat capsized.

6. Implications for Future Work

On the basis of these preliminary results, we suggest that a submarine landslide, which likely occurred on the western slope of Toyama Bay, may have been the source of the unusual tidal surges (Fig. 4(b)). This tidal surge may have caused the boat to capsize in Toyama Bay, although it is still uncertain whether the 10-cm height of the wave would have been capable of inducing the capsize of the boat. Further careful research is required to clarify the physical process of the capsize of the boat based on the details of the boat (e.g., size, weight, and structure) as well as the flow characteristics of the unusual tidal surges.

As previously stated, to confirm that the submarine landslide did occur, we require a sounding survey and core-drilling program in the channels of Toyama Bay. Sedimentary analysis of the deposits in and around the channels and an investigation of their heavy metal concentrations would provide useful data for investigating the distribution of the sediments involved in the possible submarine landslide. Geochemical analysis by Imai *et al.* (1997) shows that concentrations of heavy metals such as Pb and Zn are exceptionally high around the southern landward margin of Toyama Bay (Fig. 4(d)), the likely source area of the submarine landslide that may have occurred as a result of the 2007 Noto Hanto Earthquake.

Although our landslide model broadly reproduced the observed tidal records, with the exception of those at the Toyama observatory, the wave periods we calculated at each observatory were considerably shorter than those of the observed records (Fig. 5). These results were to be expected, because the period of the wave generated by a submarine landslide is closely related to the scale, density, and initial velocity of the landslide (e.g., Matsui *et al.*, 2002). However, our preliminary model has not been included these effects. Thus, these data must be investigated by using geological methods to allow further, more detailed numerical implementation of a landslide-generated wave model.

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