SEVERE EROSION OF SANDBAR AT UNOSUMAI RIVER MOUTH, IWATE, DUE TO 2011 TOHOKU TSUNAMI

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Abstract

The 2011 off the Pacific coast of Tohoku Earthquake Tsunami brought considerable changes in topography especially at low plains and river mouths. A sandbar at Unosumai River mouth was flushed by the tsunami and it was not recovered. In the present study, bathymetry and topography changes around the sandbar are examined. The amount of sediment deposition was estimated from Laser-Profiler data and the collected debris. Since the amount of erosion dominates the volume of deposition in inland, the majority of sandbar material was considered to be transported offshore. The erosion mechanism was investigated through numerical calculation for the tsunami flow. Very high Shields number was calculated near the sandbar and it is considered that the deep trench found at the former sandbar location was created by this strong flow.

Key words: 2011 Tohoku Tsunami, topographic change, river mouth, sandbar erosion, Unosumai River, Otsuchi Bay

1. Introduction

On 11 March 2011, a magnitude Mw = 9.0 earthquake, the 2011 off the Pacific coast of Tohoku Earthquake, occurred off the coast of Japan's Tohoku region (Japan Meteorological Agency, 2012). It generated a huge tsunami, the 2011 off the Pacific coast of Tohoku Earthquake Tsunami (2011 Tohoku Tsunami), which caused catastrophic damage and loss of life along the intricate coastline of Japan's Tohoku (North-East) region. The primary reason was the large tsunami magnitude with water surface elevations significantly exceeding expected and design tsunami heights. According to the field surveys, the tsunami heights of the 2011 Tohoku Tsunami exceeded those of the past three major tsunamis in the region (Mori et al., 2012).

The tsunami destroyed coastal structures and essential port facilities such as seawalls, breakwaters and quays at uncountable number of places. It also brought considerable changes in natural topography especially at low plains and river mouths. Sediment deposition at lowland areas was widely observed after the tsunami and sandbars at some river mouths which were directly exposed to the tsunami were flushed. It was however found that the lost sandbars were being quickly recovered for majority of the small revers flowing to the Pacific Ocean. It can be considered that the sandbars have been recovered by relatively large wave energy as well as heavy rainfalls.

Unosumai River which locates at the innermost part of Otsuchi Bay, Iwate (Fig. 1) used to have a moderate size of sandbar (sandspit) known as Nehama Beach at its mouth. Since the sandbar was at the seaside of a tsunami seawall (dyke) constructed at the left side of the river, it was thoroughly exposed to the incoming tsunami and completely flushed out. And it was not recovered at all after more than two years from the event. In the present study, bathymetry and topography changes by the tsunami around the

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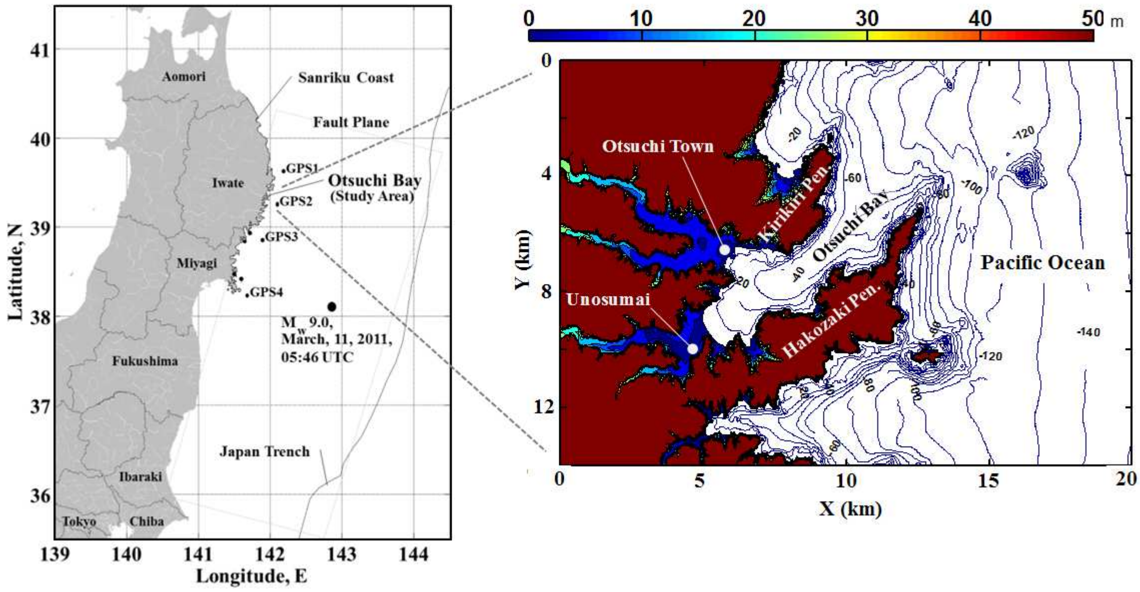

Figure 1. Left: Location of Otsuchi Bay with relation to the epi-center of the 2011 off the Pacific coast of Tohoku Earthquake. Right: The area forms a ria-type coast. Otsuchi Bay is surrounded by two peninsulas and Unosumai River locates at the innermost part of the bay.

sandbar are investigated through satellite images, sediment sampling and a bathymetry survey. Then amount of transported sediment is roughly estimated from amount of tsunami debris left landward, a comparison of detailed topography surveys and evaluation of eroded volume under the water. The mechanism of erosion is investigated through numerical calculation for the tsunami flow.

2. Erosion of Sandbar at Unosumai River Mouth

2.1. *Tsunami height and inundated area along Unosumai River*

Figure 2 and 3 show satellite images at Unosumai River mouth and the sandbar before and after the tsunami. Unosumai River is a small river whose length is about 6.2 km. The dyke at the left bank of the river was constructed until 1950', which fixed the river main flow at the present position. Before that, the river went rather straight to the coast and had created a few river channels which still remain as old river channels in Katagishi lowland area just behind the collapsed seawall. It is not sure when the sandbar was created, but it was already drawn in a similar form of 2011 on a topography map issued in 1913.

The tsunami height at Unosumai and Katagishi areas was around 12 to 14 m indicated by circles with numbers. It was more than twice of the height of tsunami seawall (design height: 6.4 m above M.S.L.) and Unosumai area which spread through the right bank (south) of the river got catastrophic damages. The lowland areas shown in Fig. 2 (or Fig. 3) were almost all inundated. The situations were similar in nearby towns (see e.g. Okayasu et al., 2012).

2.2. *Seawall collapse and topographic change at Unosumai River mouth*

By comparing Figs. 2 and 3, it was found that the tsunami collapsed a seawall built along the left bank of Unosumai River which flowed between the seawall and the sandbar. The seawalls had concrete covering on three faces (both sides and top) and were serving also as river dykes. Since the length of the sandbar was about 800 m and the averaged width was around 120 m, the lost area of sandbar was approximately 1.0×10^5 m^2 which is very large for the small river. A sand accretion found at the northwest of the original sandbar use to be the river channel. Since the deposition was not observed in a satellite image taken just after the tsunami, it is considered that it was created by wave action relatively in a short time. The lowland around the seawall was also under water, but it is not clear whether it was caused by the erosion due to the tsunami flow or by the subsidence due to the tectonic movement.

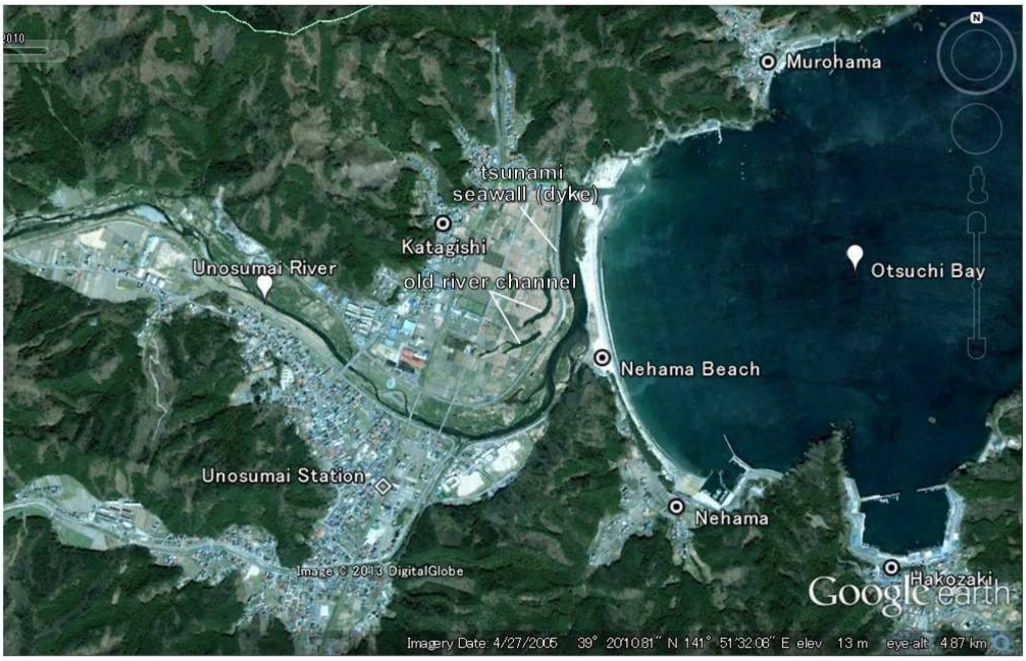

Figure 2. Satellite image of Unosumai River mouth and its sandbar (Nehama Beach, L = 800 m) before the 2011 Tohoku Tsunami. There can be seen a few old river channels just west of Nehama Beach. The tsunami seawalls working also as river dykes were constructed both sides of the river. The one at the left bank of the river was extended to protect Katagishi Area. The river went through between the seawall and Nehama Beach and flowed out at the northernmost point. (Image processed by Google Earth).

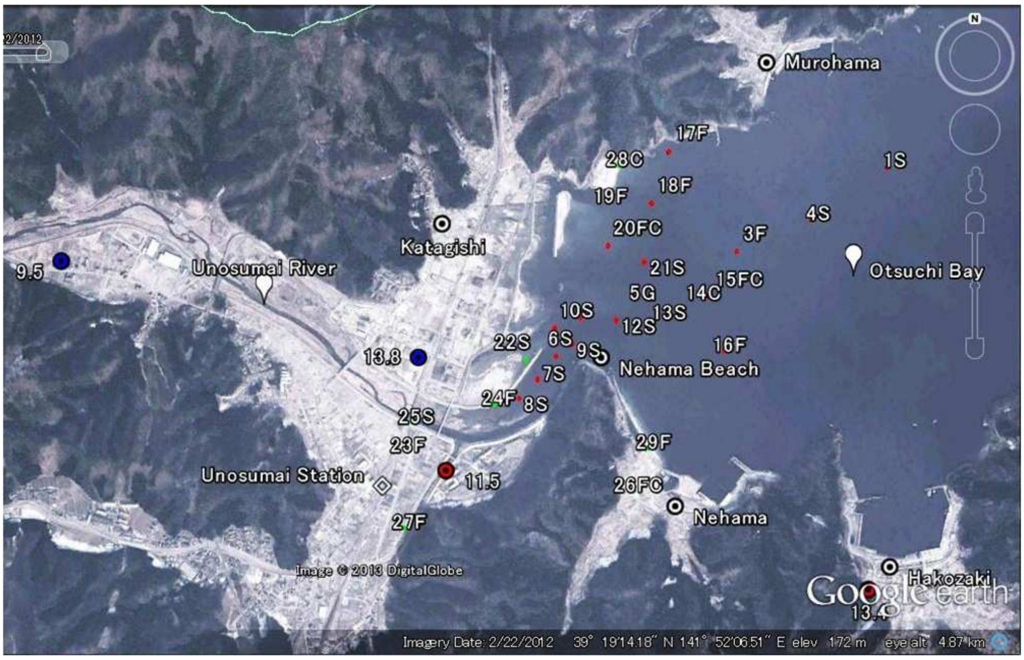

Figure 3. Satellite image of Unosumai River mouth and its sandbar after the 2011 Tohoku Tsunami. The sandbar was completely flushed. Numbers beside blue and red large circles are the measured tsunami trace heights (unit: m). Red and green small dots show positions of sediment sampling. Letters after numbers (Position #) stand for; S: silt or clay, F: fine sand, C: coarse sand, G: gravel. (Image processed by Google Earth).

3. Deposition and Erosion Balance on Sediment

To consider recovery processes of the sandbar, whereabouts of lost sand should be known. Since the size of Unosumai River is very small and the upstream area is artificially protected, the amount of sediment discharge is supposed to be small. Rivers flowing to an open ocean are exposed to large wave energy flux that actually recovered some of sandbars lost by the 2011 Tohoku Tsunami within a year or so, but Unosumai River is located at the innermost of Otsuchi Bay where wave height is not that much. Thus, if the lost sediment is not at the nearby sea bottom, it cannot be expected that the sandbar will recover soon.

3.1. *Volume evaluated by laser-profiler data*

The Ministry of Land, Infrastructure, Transport and Tourism, Japan performed Laser-Profiler (airborne LiDAR) measurements with 2 m by 2 m resolution (in horizontal directions) before and after the 2011 Tohoku Tsunami. The Laser-Profiler (LP) data after the event were obtained in April 2011. The left panel of Fig. 4 gives the LP data before the event. Influences of buildings and trees are excluded by a certain algorism with which bridges are excluded but embankments are not. The seawalls (dykes) along the river are clearly seen in the figure. The right panel of the figure is that measured after the event. The sandbar was lost and effects of erosion by tsunami and subsidence by earthquake is clearly observed. Liquefaction might cause additional subsidence but it isn't known in this area. A small fraction of land seen in the east of the left seawall was a vestige of the sandbar, which latter moved and attached to the seawall.

In order to estimate an amount of sediment deposited in land area, a differential of two sets of LP data was calculated. The left panel of Fig. 5 shows the simple differential of two data. Since the tectonic movement is not negligible for the fine resolution of data, the differential shows very large positive and negative variations (more than ± 2 m) especially in hilly areas. A record obtained by Geospatial Information Authority of Japan (2013) for a nearby bench mark gives a movement of about 2.4 m in the east direction and 1.6 m in the south direction until April 2011. Since interpolation may lose the precision, a 1 grid (east, equivalent to 2 m) and 1 grid (south) horizontal adjustment was adopted to obtain the best match for the differential of the two data. The data also shows general tendency of negative values in the lowland area. Geospatial Information Authority of Japan also provides information that a bench mark located at Katagishi area showed 60 cm of subsidence until April 2011 and was almost stable afterward.

The right panel of Fig. 5 is the result of the adjustment with consideration of subsidence. The data still show relatively large variations in the hilly areas, but the main interest of the research is in the lowland and the errors caused by the horizontal movement would be cancelled in theory except borders. On the contrary, the adjustment in the vertical direction directly affects the precision of the estimate. It is however that the top of the residual seawall indicates almost white (neutral), which may show the adjustment was appropriate. The straight line runs through the lowland north to south is JR Yamada line whose embankment was severely damaged by the tsunami.

In the figure, the lowland generally shows slight accretion, which suggests sedimentation by the tsunami. The net volume of sediment deposited on the lowland below 20 m in altitude was roughly calculated from the LP data as 1.6×10^5 m^3 (equivalent to 3×10^5 ton). It should be noted here that the calculated amount is quite sensitive to the value of subsidence and 1 cm of variation of it corresponds to a volume of 2×10^4 m^3. The precision of the bench mark survey was within 1 cm, but there may be an effect of liquefaction or other similar factors.

3.2. *Volume estimated from amount of collected debris*

According to the business specification for disaster waste treatment (Kamaishi City, 2012) for Unosumai and Katagishi areas, the possible amount of tsunami deposition in the debris was about 5×10^4 m^3 which was one third of the estimated value in the previous section. The evaluation depended on the past statistics for the ratio of sediment in disaster wastes and was very rough estimation. Another factor might be that debris contained only sediment was usually left untouched in many places other than the roads and public areas. The amount of left sediment is unknown, but the calculated values from the LP data and the collected debris are comparable, thus may not be far from the reality.

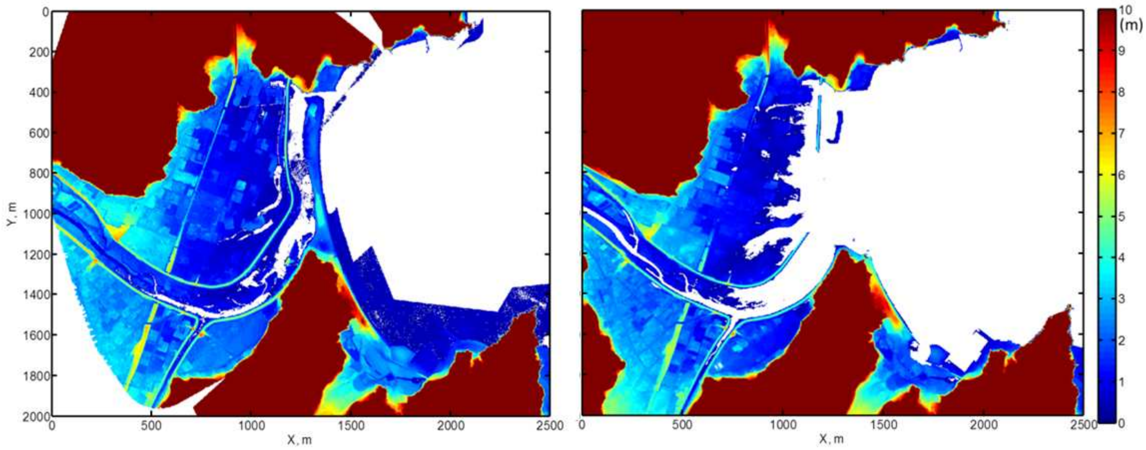

Figure 4. 2 m by 2 m resolution Laser-Profiler (LP) data of ground level provided by the Ministry of Land, Infrastructure, Transport and Tourism, Japan for topography before 2011 Tohoku Tsunami (Left) and after (Right). The water area is left blank (or recorded as 0 m for altitude).

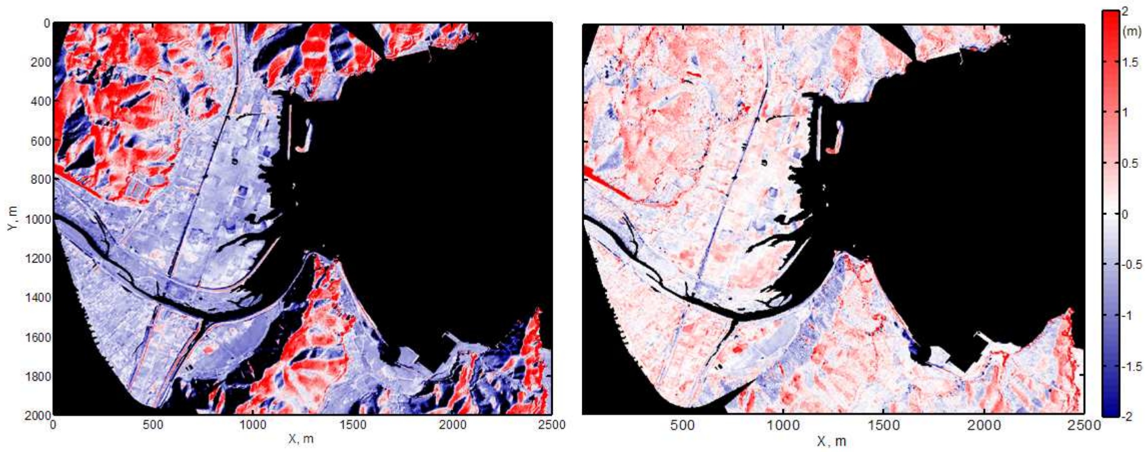

Figure 5. Left: Differential between LP data before 2011 Tsunami and after 2011 Tsunami. The simple differential gives large positive variation (accretion) for south and east faces of slopes and north and west faces show negative values (erosion) because of the horizontal tectonic movement by the earthquake. General tendency of negative values on the flat lowland is caused by the vertical tectonic movement (subsidence). Right: The best match for the least variation on the hilly slopes. The subsidence was considered to be 60 cm from elevation change at a bench mark in Katagishi area measured by the Geospatial Information Authority of Japan.

3.3. *Nearshore bathymetry change and volume of erosion*

Figure 6 gives a result of bathymetrical survey around the former sandbar location conducted in June 2012. The depth was measured by a combination of a hand-held GPS and a sounding instrument installed on a small research boat. Two deep trenches are found further along the old river channels suggesting strong return flow there. An amount of eroded sand was evaluated from the figure. The depth was obtained every 30 m in the horizontal directions from the figure and volume was calculated for areas whose altitude had been over 0 before the tsunami. This means that the erosion at sea and river bottom was not counted if the location had been under water before the event.

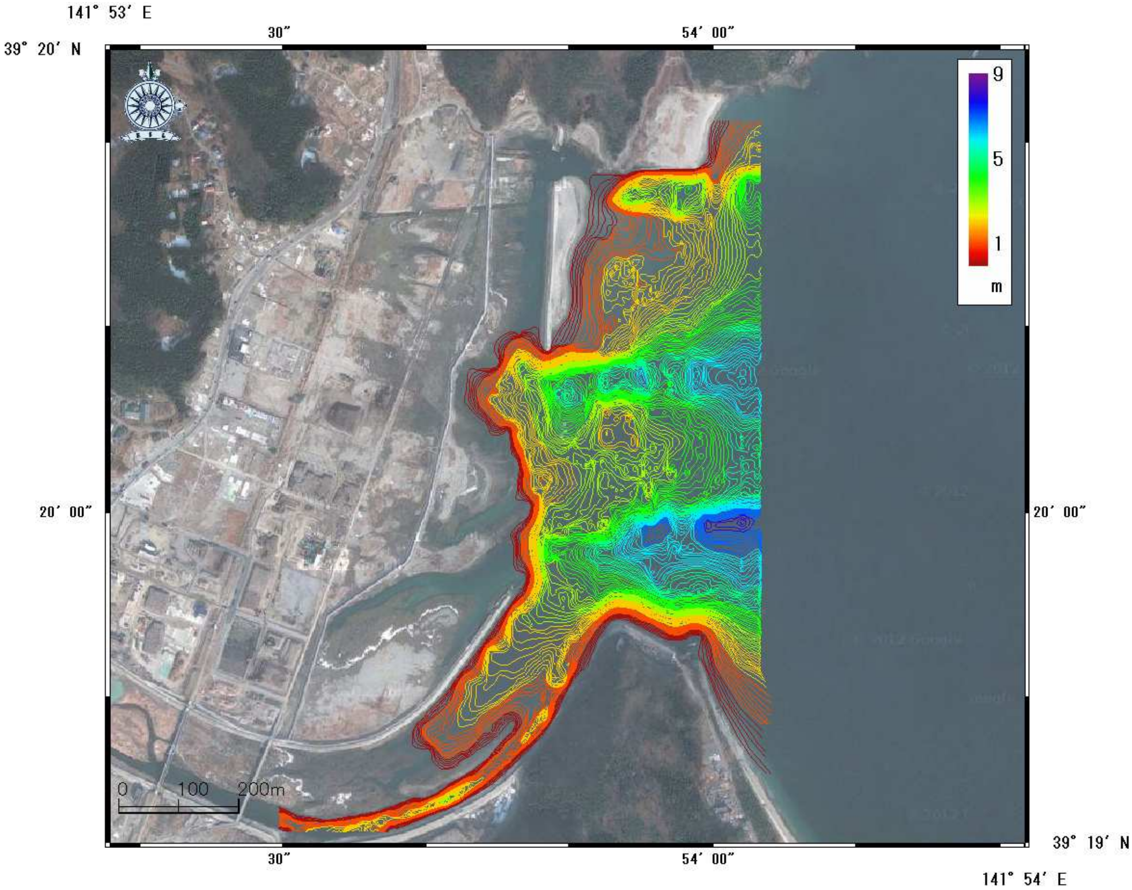

Figure 6. Bathymetry data obtained by depth measurement in June 2012. It is clearly seen that a few deep trenches were created further along the old river channels. It is found from the bathymetry that the sandbar was completely washed away.

Rough calculation gives 7×10^5 m^3 which is very large number. The value doesn't include sediment over 0 m in altitude and that was already taken into account in the volume described in the previous section. Considering the existence of deep trenches which may extend to the deeper place, the amount of erosion dominates the balance of sediment movement in the Unosumai nearshore region. It can be concluded that the majority of sediment which had once formed Nehama Beach sandbar was not transported onshore but offshore. From the bathymetry survey result, it is difficult to expect that the sediment stays in the vicinity of the former sandbar location.

3.4. *Distribution of sediment diameter in shallow water region*

In order to see composition of sediment on the seabed, sediment sampling from land and sea bottom surface was performed in September 2012. Sediment was collected by using a Smith-McIntyre bottom sampler for seabed. The composition was analyzed with sieves for larger material (d > 1.0mm) and a Laser diffraction particle-size analyzer for smaller compositions. Central diameter d_{50} for each sample was obtained from grain size distribution. Locations of sampling and classifications of diameter for sediment are shown in Fig. 1. In the figure, letters after the location numbers show S: silt or clay, F: fine sand, C: coarse sand, G: gravel.

From the figure, it is found that sediment transported onshore and deposited on the lowland area shows relatively small diameter. The diameter along the southern deep trench tends to be larger, which may suggest that the flow along the trenches were strong and might expose the old river bottom or sea bottom formed several thousand years ago.

4. Numerical Simulation of Flow and Erosion Mechanism

The flush process of the sandbar by the tsunami was investigated through numerical simulation. The calculation was based on a set of non-linear shallow water equations with bottom friction terms based on the Manning's formulation. The grid spacing was 20 m and the water surface elevations measured by GPS buoys installed at offshore (see Fig. 1) were given as the incident wave at the offshore boundary. Other details are described in Shimozono et al. (2012).

4.1. *Topographic features and characteristics of tsunami flow*

Figure 7 shows calculated water surface elevation and magnitude of velocity at an uprush phase. For the uprush phase, the tsunami flow went inland through whole coastline (Nehama Beach) open to the bay. The calculated surface elevation shows almost 20 m of runup at the end of Nehama village next to Unosumai, which agrees well to the survey record (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2013). The distribution of velocity magnitude indicates that the contraction of flow at the south end of Nehama Beach created strong current which is supposed to flush the deposited sand there and transported it inland.

Snapshots of surface elevations and distributions of flow magnitude for the drawdown phases are given in Fig. 8. At time = 47 min., the flow reached to the innermost of Unosumai area and the drawback was already started at the original shoreline. The width of the flow at Nehama Beach is narrower than that at the uprush phase and the large depression of surface which suggests generation of super-critical flow on the sandbar can be seen. The flow magnitude correspondently shows very large velocity which is more than 10 m/s on and offshore the sandbar. The major part of the flow was generated by the super-critical flow on the sandbar, but the return flow is concentrated at the old river channels which supposed to be responsible for the collapse of the seawall and probably making the deep trenches in a shallow region where once the sandbar was.

At time = 53.7 min., the water surface shows the max drawdown which less than -10m in the center of Otsuchi Bay. The water is continuously running from the inland and passed through the lower place of the coast. The absolute value of velocity on the sandbar decreased but the area of large velocity is considerably extended to deeper place toward the center of the bay. Although the two-dimensional flow pattern in the bay is much affected by the assumptions and coefficients artificially given in the numerical model, surface elevation is less sensitive to the model setting. Thus the stretch of the large velocity region toward the center of bay is considered to be appropriate.

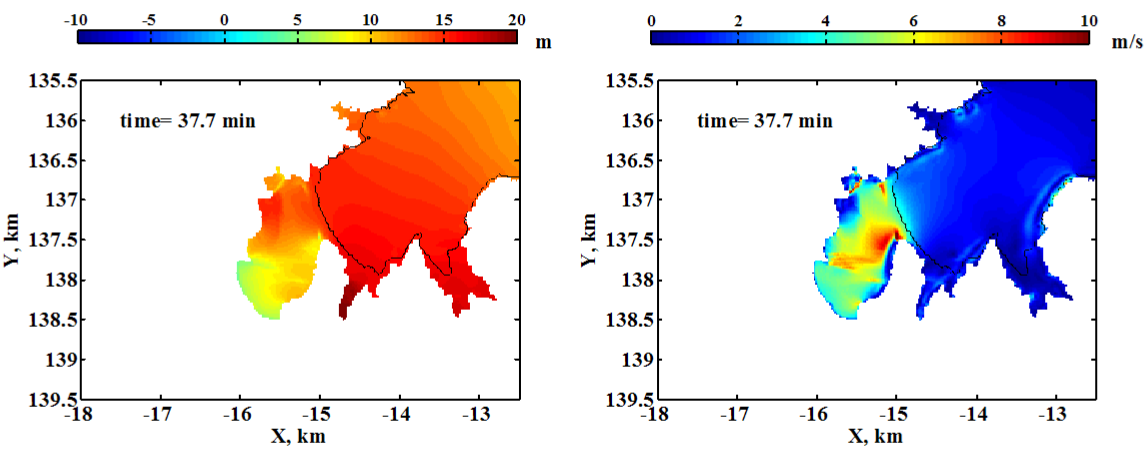

Figure 7. Left: Calculation result of water surface elevation at the uprush phase of the first tsunami. The time counts for the elapsed time from the occurrence of earthquake. It is found that the tsunami overflowed from the whole stretch of Nehama Beach. Right: Magnitude of velocity at the same phase. Flow velocity at the south end of Nehama Beach was so large that sediment deposited there was supposed to be transported it inland.

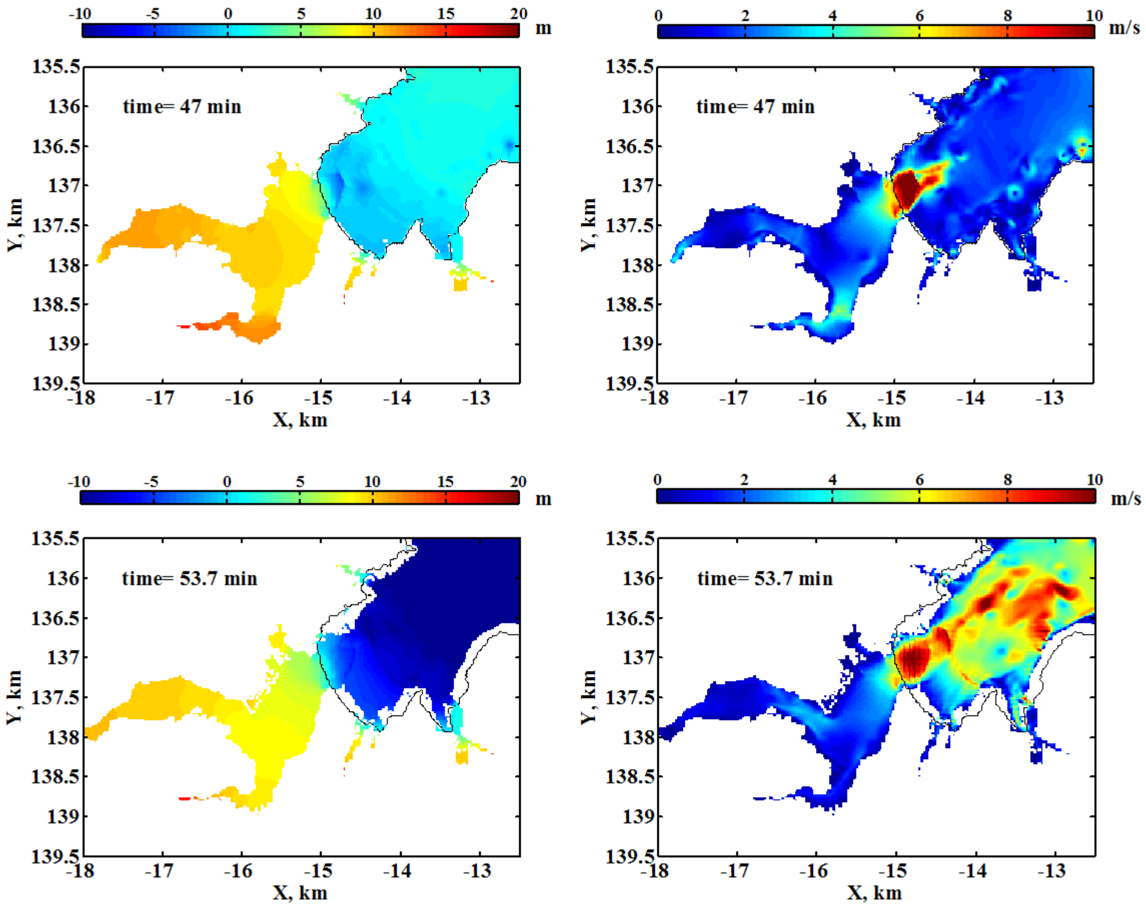

Figure 8. Top-left: Calculation result of water surface elevation at the early drawdown phase time = 47 min. The largest runup at the innermost of Unosumai area shows close to 15 m which was a little overestimate. The return flow passes a narrow low area at Nehama Beach and creates large depression at offshore side of the sandbar. Top-right: Magnitude of velocity at the same phase time = 47 min. Flow velocity on the sandbar is very large and the offshore part of the sandbar is even larger. Bottom-left: Water surface elevation at drawdown phase time = 53.7 min. The drawdown in the center of the bay reaches to -10 m. Bottom-right: Magnitude of velocity at the same phase time = 53.7 min. The strong current extends to the center of the bay which may cause significant erosion in the shallow water region.

4.2. *Bottom sheer stress distribution and eroded pattern*

In order to investigate the movability of sediment, Shields number was calculated for diameters of 1 mm (representing sand) and 10 mm (representing gravel) at a phase of time = 47 min. The left panel of Fig. 9 gives distribution for the representative sediment diameter = 1 mm. As anticipated from the previous figures, very high Shields number was observed near the sandbar. The maximum number is well beyond 10, which means the sediment was rapidly transported offshore under the sheet flow regime. It is found in the figure that two streaks of regions with large Shields number exist. One goes from the location of an old river channel to offshore, the other was at the north end of sandbar. Since the position of the former streak coincides to the location of the southern deep trench found by the bathymetry survey, it is considered that the deep trench was created by this strong flow. The latter one was probably generated due to contraction of the flow inland.

A distribution of Shields number for a diameter of 10 mm is given in the right panel. The distribution shows that even gravel can easily be transported offshore. The position No.5 of the bottom sampling shown

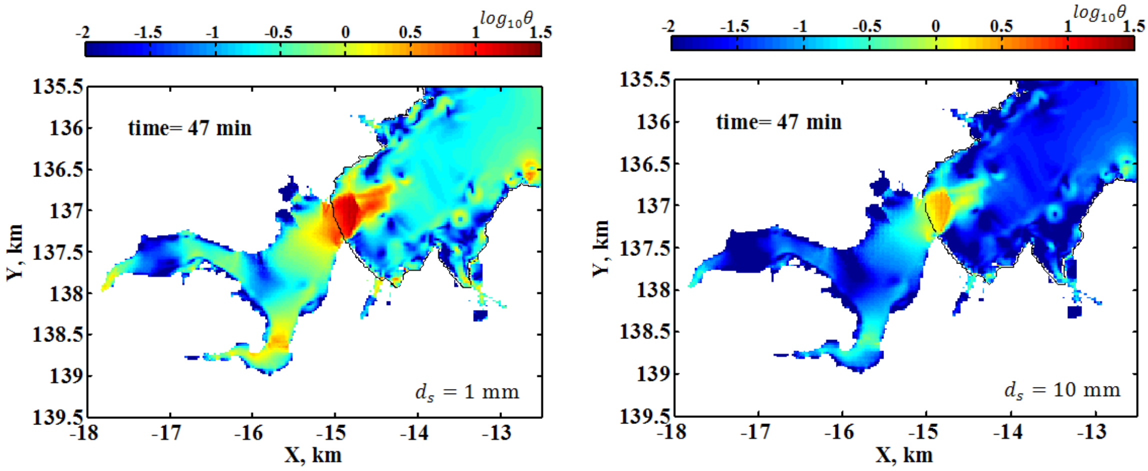

Figure 9. Left: Snapshot of Shields number distribution for the representative sediment diameter = 1 mm at the phase of time = 47 min. The Shields number is very large near the sandbar. Two streaks of large value are observed. One starts from the location of the old river channel to offshore. The position coincides to one of the deep trenches found by the bathymetry survey. Right: Shields parameter distribution for diameter = 10 mm. The distribution shows that even gravels easily transported offshore.

in Fig. 3 is located beside the trench and the sample was classified as gravel. It is considered that the sea bottom was easily eroded with such a large Shields number even if it consisted of gravel. As far as the calculation is referred, it is natural that the sandbar was severely eroded and the sand was transported far offshore together with larger materials which might exist underneath of the sandbar.

5. Conclusions

A large sandbar at Unosumai River mouth which is located at the innermost part of Otsuchi Bay, Iwate was completely flushed out by the 2011 off the Pacific coast of Tohoku Earthquake Tsunami and it has not been recovered at all after more than two years from the event. In the present study, bathymetry and topography changes around the sandbar are examined. The amount of sediment deposition was estimated from Laser-Profiler data and the collected debris. The erosion mechanism was investigated through sediment sampling and numerical calculation for the tsunami flow. The conclusions of the study are summarized as follows.

1) The lost area of sandbar was approximately 1.0×10^5 m^2 which is very large for the small river.
2) The net volume of sediment deposited on the lowland below 20 m in altitude was roughly calculated as 1.6×10^5 m^3 from the LP data, whereas the possible amount of deposition estimated from the collected debris was about 5×10^4 m^3.
3) Rough calculation from the bathymetry survey gave 7×10^5 m^3 of erosion at the sandbar location. Since the amount dominates the estimated volume of deposition in inland, the majority of sandbar material was considered to be transported offshore.
4) In the flow simulation, the tsunami flow went inland through whole coastline for uprush phases, but it was concentrated through the narrower low place for drawdown phases.
5) Very high Shields number was calculated near the sandbar. From the numerical analysis, it is considered that the deep trench was created by this strong flow

Further studies are expected for sediment discharge from the upstream of Unosumai River, a bathymetry survey in the deeper area of Otsuchi Bay, core samplings at sea bottom to reveal layers of materials Nearshore and wave climates and resultant wave forces on sediment in Otsuchi bay to investigate the sediment movement by the wave action.

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References

Geospatial Information Authority, 2013. http://www.gsi.go.jp/chibankansi/chikakukansi40005.html (referred on Apr. 1, 2013).

Kamaishi City, 2012. Kamaishi disaster waste treatment (Katagishi recycling process) specification, Kamaishi City.

Japan Meteorological Agency, 2012. http://www.jma.go.jp/jma/en/2011_Earthquake/2011_Earthquake.html (referred on Sep. 15, 2012).

Mori, N., T. Takahashi, and the 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2012. Nationwide post event survey and analysis of the 2011 Tohoku Earthquake Tsunami, *Coastal Engineering Journal*, JSCE, 54, 1250001 (27p).

Okayasu A., T. Shimozono, S. Sato, Y. Tajima, H. Liu, T. Takagawa and H. M. Fritz, 2012. 2011 Tohoku tsunami runup and devastating damages around Yamada Bay, Iwate: surveys and numerical simulation, *Proc. Int. Conf. on* C*oastal Engineering*, 33.

Shimozono, T., S. Sato, A. Okayasu, Y. Tajima, H. M. Fritz, H. Liu, and T. Takagawa, 2012. Propagation and inundation characteristics of the 2011 Tohoku tsunami on the central Sanriku coast, *Coastal Engineering Journal*, JSCE, 54, 1250004 (17p).

The 2011 Tohoku Earthquake Tsunami Joint Survey Group. 2013. http://www.coastal.jp/tsunami2011/ index.php? Field survey results (referred on April. 1, 2013).