QUANTITATIVE ANALYSIS ON THE TSUNAMI INUNDATION AREA AND EROSION ALONG THE ABUKUMAGAWA RIVER AT THE GREAT EAST JAPAN EARTHQUAKE

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Abstract

The tsunami caused by the Great East Japan Earthquake on 11 March 2011, broke most of the sea embankment and coastal vegetation belt and caused catastrophic damage to people and buildings in the Tohoku and Kanto regions of Japan. Field surveys were conducted to elucidate the volume of embankment erosion and their hinterlands (residential area) by tsunami propagation in river channels and overtopping of embankments. Ten rivers were selected for the field investigation. This study focuses on the situation around the Abukumagawa River where severe erosion due to overtopping of embankments was occurred. To elucidate the relationship between the scoured area and the tsunami overtopping time, numerical simulation was conducted around the river mouth area of Abukumagawa River including the hinterland. For reproducing the Japanese tsunami, non-linear long-wave equations and a fault movement model were used in this study. For calculating tsunami from large region where fault motion occurred to small region where tsunami inundation and overtopping from river embankment occurred, five different regions with different grid size were set and flux and tsunami height in boundary grid were interpolated from large size grid to small size grid by nesting method. This simulation validated in comparison with the observed data and simulated one as to maximum water level near Abukumagawa River.
The simulation reproduced well the tsunami water depth and inundation area within a reasonable limit, and showed a clear positive tendency between the time while tsunami overflow occurred and the size of scoured region on and around embankments measured by the post tsunami survey in April 2011. However, the volume of embankment erosion was greatly affected by the locality along the river, i.e. meandering, sand bar at river mouth, obstruction by a bridge, even when the tsunami-overtopping time was similar. This indicates that erosion volume due to overtopping from embankments is affected not only by overtopping time but also by the locality, and the mechanism should be included in future.

Keywords: overtopping, embankment, erosion

1. INTRODUCTION

The tsunami generated by the Great East Japan Earthquake at 14:46 JST on 11 March 2011 with a magnitude of 9.0 broke many of the sea walls (tsunami gates, large embankments), and caused catastrophic damage to both human life and socioeconomic property in the Tohoku regions of Japan. Information about this earthquake and tsunami can be obtained from Mimura et al. (2011) and Takahashi et al. (2011).

When a large tsunami reaches a shore, most of it slows, increases in height, and runs up towards the land with tremendous energy, causing massive destruction on the coast and in the hinterlands. Extensive experimental (Peregrine, 1967; Madsen and Mei, 1969) and analytical (Benjamin, 1972) studies have shown that tsunamis are also propagated far upstream in rivers because a solitary wave like a tsunami propagates without changing its shape and speed in a straight channel of uniform depth and width.

In an actual tsunami, river morphology greatly affects the propagation (Tanaka et al., 2012). Although the propagation of solitary waves through curved shallow water channels was investigated by numerical simulations and the deformation of the wave at the outer bank has been described (Shi et al., 1998; Yuhi et al., 2000), the disastrous results of propagation of an actual tsunami in a curved channel were not reported in previous research. In addition, it is very important to elucidate the role of inland embankments of roads, railways, and channels along the coast in mitigating the tsunami or changing tsunami direction.

Tanaka et al. (2012) conducted field survey to elucidate the damage to river embankments and their hinterlands (residential area) by tsunami propagation in river channels and overtopping of embankments. Abukumagawa River in Miyagi Pref. was selected for the field investigation. In the hinterlands, the tsunami came from two directions, coast and river, and the situation, including the evacuation of people, became complex. The research pointed out the necessity to identify locations of river embankments that can be easily overtopped by a tsunami in different tsunami conditions. The quantitative information between the damage situation of river embankment and the overflowing tsunami condition, i.e. overflowing tsunami water depth, duration of overtopping of embankment, was still not obtained in Tanaka et al. (2012).

Therefore, the objectives of this study were: 1) to elucidate the effects of river morphology on the tsunami overtopping the embankment, and the damage in the hinterlands, and 2) to assess the relationship between embankment damage and the overtopping time calculated by numerical simulation.

For the objectives, field investigation was conducted near the river mouth of the Abukumagawa River in Miyagi Pref., and numerical simulations were conducted for obtaining the quantitative information between tsunami the overtopping from river embankment and the damage occurred at the site.

2. MATERIALS AND METHODS

2.1 Site locations and measurement method

The field investigations were carried out in April and May 2011 around Abukumagawa River. The locations are shown in Figure 1.

Figure 1: Location of Abukumagawa River

At our field investigation, the tsunami water depth was determined by the height of scars made by collisions of debris on tree trunks, water marks on the walls, or debris on the roofs of damaged houses. In addition, overtopping depth from river to hinterland was surveyed as possible. The tsunami directions were analyzed by the directions in which trees and fences were bent, the location of broken walls of houses, and scoured regions behind embankments or around houses. Estimated tsunami water depths of the river or on the embankment and that in the hinterlands were also compared to judge the dominant tsunami directions. The scoured volume of river embankment and hinterlands by overtopping tsunami were measured by the scoured depths and widths as shown in Figure 2.

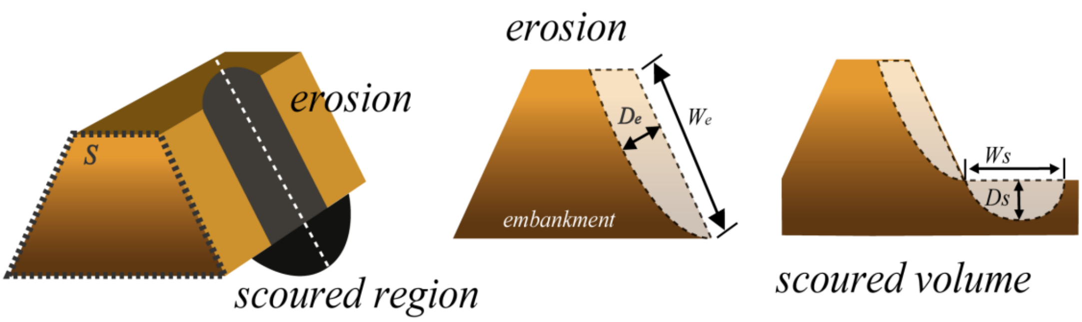

Figure 2: Definition of observed parameters regarding erosion and scouring.
Erosion ratio = $D_eW_e/S\times100$ (%), Scoured volume per unit length = D_sW_s (m^3), where, S: area of the cross section of embankment, D_e: depth of the eroded area on the slope of embankment, W_e: length of the eroded area on the slope, D_s: depth of the scoured region on hinterland, W_s: length of the scoured region on hinterland

2.2 Numerical simulation

For calculating the tsunami propagation, five calculation regions with different grid size were used as shown in Figure 3. In this study, the grid size of Region A, B, C, D and E was set as 1350 m, 450 m, 150 m, 50 m and 16.7 m respectively. The linear long wave equations and non-linear long wave equations were applied to Region A and Region B-E, respectively. The governing equations of non-linear long wave are written as:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \tag{1}$$

$$\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x^2}{\zeta + h}\right) + \frac{\partial}{\partial y}\left(\frac{Q_x Q_y}{\zeta + h}\right) + g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{gn^2}{(\zeta + h)^{7/3}} Q_x \sqrt{Q_x^2 + Q_y^2} = 0 \tag{2}$$

$$\frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x Q_y}{\zeta + h}\right) + \frac{\partial}{\partial y}\left(\frac{Q_y^2}{\zeta + h}\right) + g(\zeta + h)\frac{\partial \zeta}{\partial y} + \frac{gn^2}{(\zeta + h)^{7/3}} Q_y \sqrt{Q_x^2 + Q_y^2} = 0 \tag{3}$$

Where, x and y are horizontal Cartesian coordinates, t is the time, ζ is the surface evaluation, h is the still water depth, Q_x and Q_y are the depth integrated flow flux components in x and y directions, g is the gravitational acceleration and n is the Manning roughness coefficient.

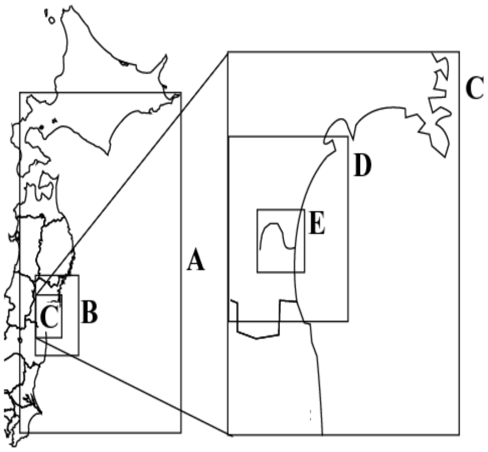

Figure 3: Location of each calculation region for the numerical simulation

Finite difference method was used for solving the flow with leap-flog method and staggered grid system. Sea surface displacements calculated by the fault model of Mansinha and Smylie (1971) were given as initial condition of the simulation. The fault parameters published by Fuji and Satake (2011) were applied in this study. The tsunami run-up to inland was calculated by method of Iwasaki and Mano (1979). As boundary condition, non-reflective wave condition was applied in Region A.

2.3 Validation of numerical model

Figure 4 shows comparison between maximum tsunami water depths investigated and the simulated tsunami depths in coastal area of the Abukumagawa River. The tsunami water depths observed by 'The 2011 Tohoku Earthquake Tsunami Joint Survey Group (2011)' were also shown in the figure. For calibrating the simulated tsunami water depths to the observed values at right and left-hand side of riverbank, and coastal area, the initial displacement of water calculated by fault parameter of Fujii and Satake (2011) was slightly modified (multiplied 0.9). Figure 5 compares the investigated tsunami water heights with simulated values along Abukumagawa River. The simulation reproduces well the tsunami water depth within a reasonable limit. Investigated tsunami height at 1.5km point from river mouth shows locally high because of the damming by the Watari-Ohasi Bridge located at the meandering part of the river. The numerical model did not include the damming effect by the bridge, so the result could not express the locally large tsunami height. On the right-hand side of the river, the fault parameter effect was small, however, on the left-hand side, the modified parameter's case (0.9 was multiplied to the fault parameter) can simulate well the actual tsunami situation. So the modified fault parameter's case was used for analyzing the tsunami propagation in the river.

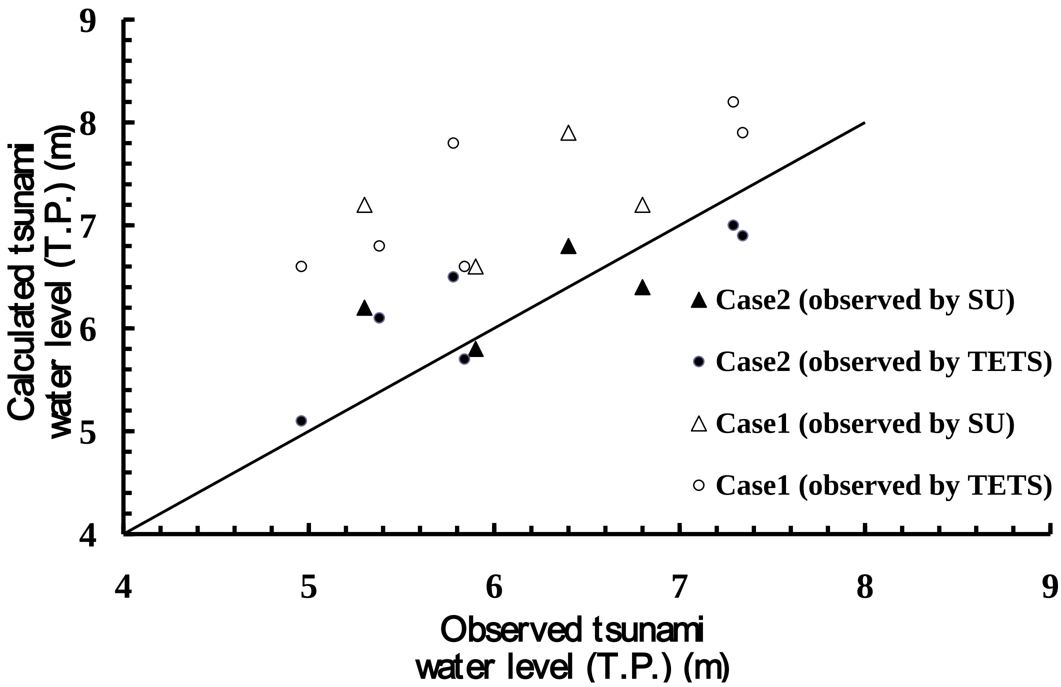

Figure 4: Comparison between observed and calculated tsunami water level in coastal area of Abukumagawa River. Case 1 and Case 2 shows the relationship between the observed tsunami water level and the calculated value using original water level displacement by Fujii and Satake(2011) and modified one, respectively. In this study, water level displacement of Case 2 was used by multiplying 0.9 to the parameter of Case 1. SU and TETS represent the Saitama University and The 2011 Tohoku Earthquake Tsunami Joint Group, respectively.

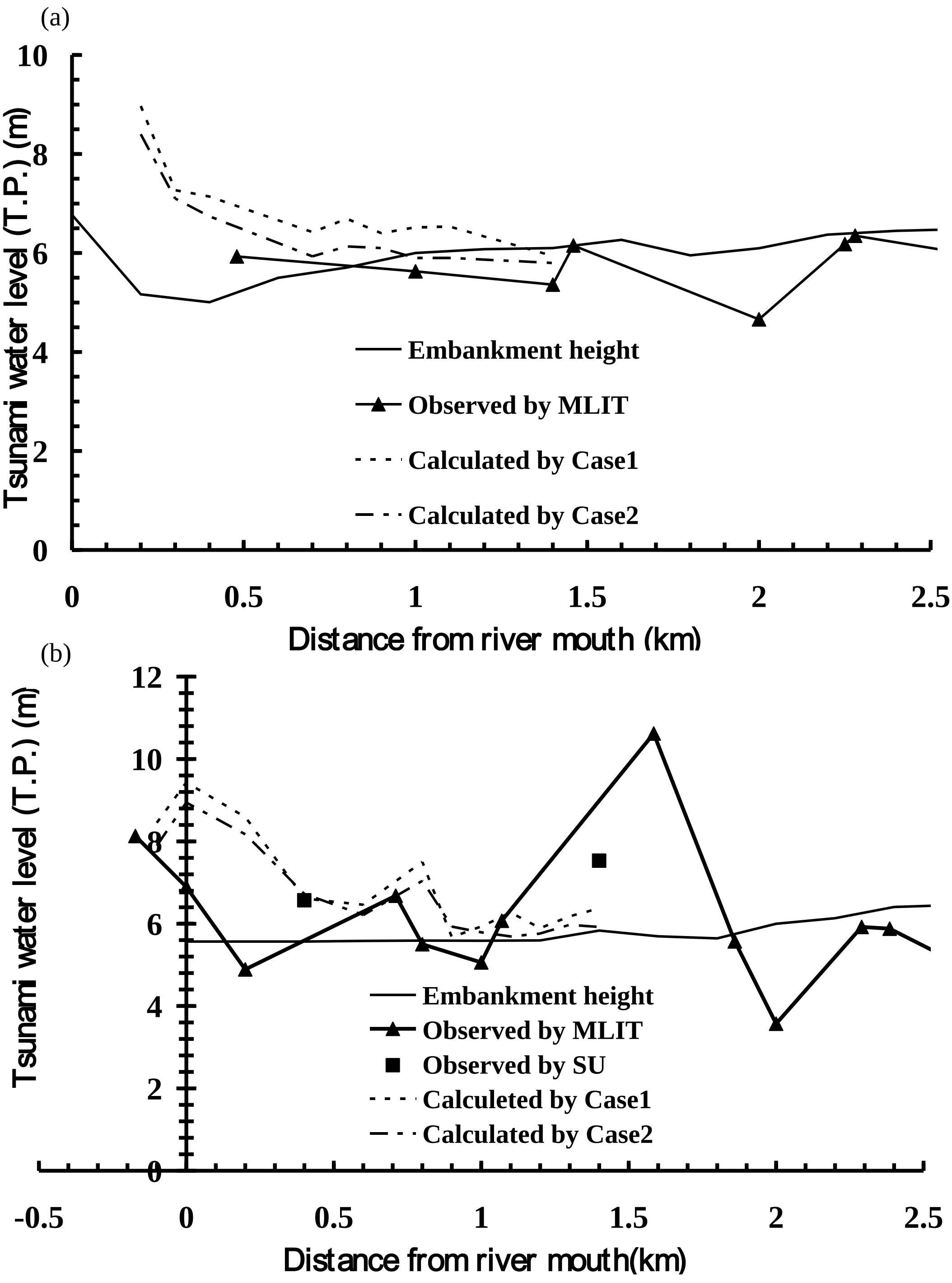

Figure 5: Comparison between the observed and calculated maximum tsunami water depths around river embankment (a) Left-side bank, (b) Right-side bank. Case 1 and Case 2 shows the relationship between the observed tsunami water level and the calculated value using original water level displacement by Fujii and Satake(2011) and modified one, respectively. In this study, water level displacement of Case 2 was used by multiplying 0.9 to the parameter of Case 1. SU and MLIT represent the Saitama University and Ministry of Land, Infrastructure, Transport and Tourism, Japan, respectively.

3. Results and discussion

3.1 Tsunami propagation and overtopping of embankment around Abukumagawa River

The direction and water depths of the tsunami inundation are shown in Figure 6. Breaching of the sea embankment was observed at location S. Near this region, the tsunami water depth was around 5.5 m and the embankment height was 4.8 m. At location B, the overtopping water depth at the top of embankment was estimated to be around 1 m based on the debris attached to the fence. Just downstream of Location A, the river embankment was also breached by direct attack of the tsunami. The overtopping from the river to the hinterland was severe at location B, but was a little less severe upstream at location C. However, the overtopping became severe again at location D. The extent of overflow was judged from the erosion of the river embankment slope and scoured regions around houses and the broken or washed-out situation of houses. The location D was on the outer-bank side of the river. Debris were attached on the girder of the Watari-ohashi Bridge at the upstream of Location D, but was not at the opposite side (inner side of the meandering) of the river embankment. There are three reasons why the location D had larger damage than C. One is that the water depth was higher at outer-bank side of the river and second is that the damming was occurred by the debris accumulation at the girder of the bridge. The third is that the overflow pattern from river embankment is different. The elevation of the road along the river was higher around location D than in location C, so the difference between the ground level of houses and the road was greater. In that case, the scouring was larger not only by the overtopping flow but also by local flow around houses. Thus, houses around location D and E were completely washed out, not by the tsunami propagated from seaward, but by the tsunami overtopping the river. Only small erosion was observed on the surface of river embankment at Location F in the left-hand side of the river, although the tsunami water depth in landside area was 2.6 m near the site. The left hand-side river embankment was almost parallel to the sea embankment because of the meandering of the river, and the tsunami inundated from sea side was assumed to be easily accumulated at the site before the tsunami current overtopped from the river. The accumulated water protected the river embankment surface from erosion by reducing the overtopping velocity because the overtopping was occurred as a submerged type.

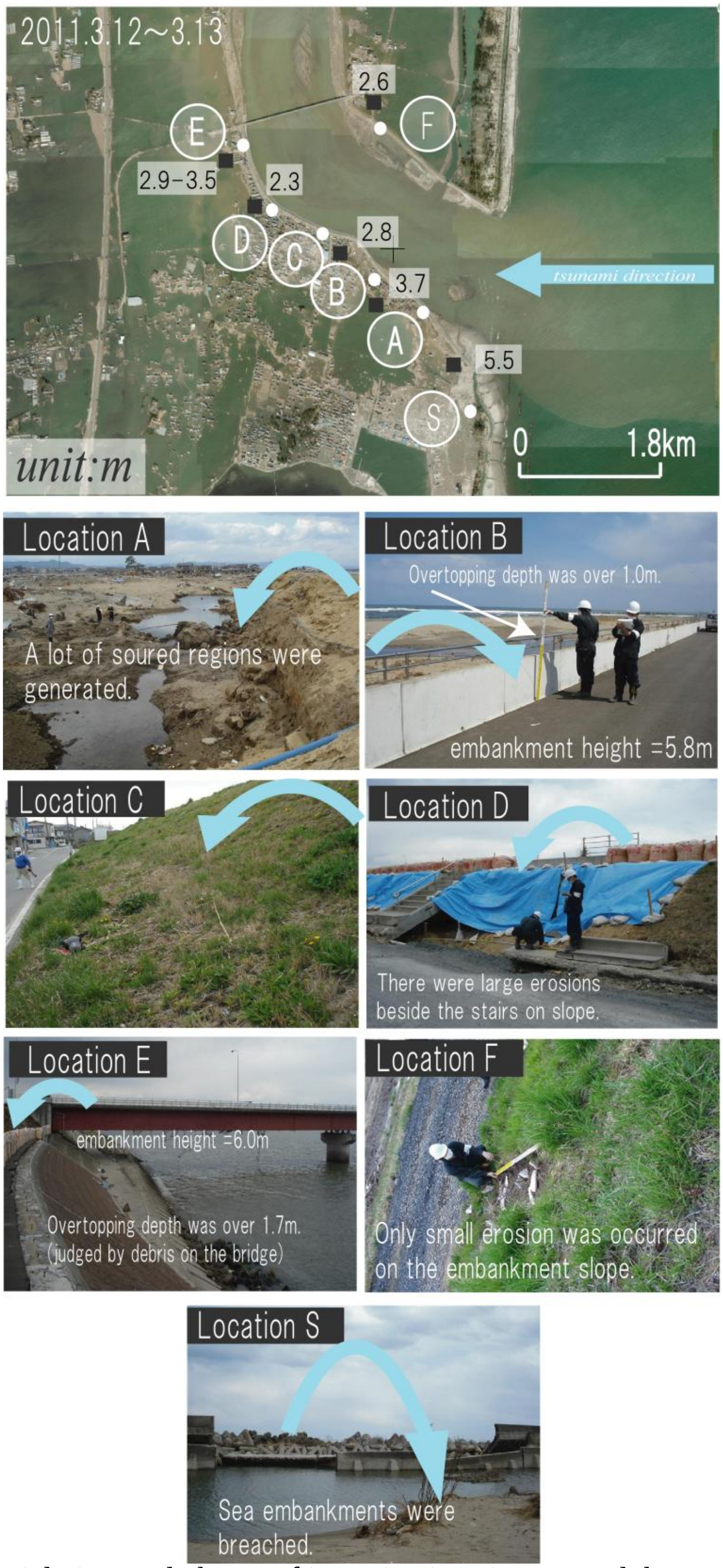

Figure 6: Aerial view and photos of investigation sites around the mouth of the Abukumagawa River. The numerical values represent the observed tsunami water depth at the closed square location. (Modified the aerial photo provided by Geospatial Information Authority of Japan)

3.2 Effect of overtopping time on the volume of scour hole and erosion of river embankment

The relationship between overtopping time and erosion ratio of river embankment defined in Figure 2 and the scoured volume are shown in Figure 7(a) and (b), respectively. In general, the damage of river embankment should be more severe with increasing overtopping time. When the overtopping time became over 400 seconds, the similar tendency was confirmed in this study. However, scoured volume and erosion ratio of river embankment were large even when overtopping time was less than 200 seconds at Location D and Location F.

Maximum tsunami water level at right-hand side of the river was measured higher than height of Watari-ohasi Bridge. The water level in front of this bridge could be increased by the resistance of bridge to the tsunami flow. However, drag force to the tsunami by this bridge was not considered in this calculation. Therefore, calculated overtopping time seemed to be underestimated in comparison with actual overtopping time. Point1, 2 and 3 in Figure 7(a) represents the data obtained at location B (Figure 6). As each point was located at the close position, almost the same calculated overtopping time was obtained. However, erosion ratio at each point was largely differed. In this location, embankment shape along the flow direction is like a fan as shown in Fig.8. Point2 and 3 located near the center of the fan. On the other hand, Point1 was a little far from center of the fan in comparison with Point2 and 3. The erosion ratio of Point2 and 3 became larger than that of Point1 because the tsunami current was concentrated to the center of the fan. In addition, as shown in Figure 8, there was large sand bar at the river mouth before the tsunami event in March 2011. The tsunami could have been leaded to left riverbank and diffracted to location C. Then there was some possibility that the wave was changed the direction to the right-hand side of river embankment and overtopped strongly at Point 2 and 3. On the other hand, the location of Point 1 was closer to this sand bar than that of Point 2 and 3. Therefore, the intensity of overtopping flow at Point 1 due to diffracted wave might become smaller. In addition, our field investigation suggested that amount of erosion was affected not only by overtopping flow but also by the structure of embankment. In case of Abukumagawa River, large erosion could be observed just the neighbor of concrete stairs installed on embankment slope. In this large earthquake, many cracks were occurred at the boundary of stairs and embankment body. Large erosions were formed by the overtopping flow into these cracks.

From the study, it is found that the overtopping time of tsunami should be reduced for reducing the volume of scour and erosion of river embankment. However, the locality of tsunami overtopping causes the large local erosion of river embankment and hinterland. Therefore, for evaluating the overtopping time accurately, effect of sand bar and structure across the river on tsunami propagation should be considered in future.

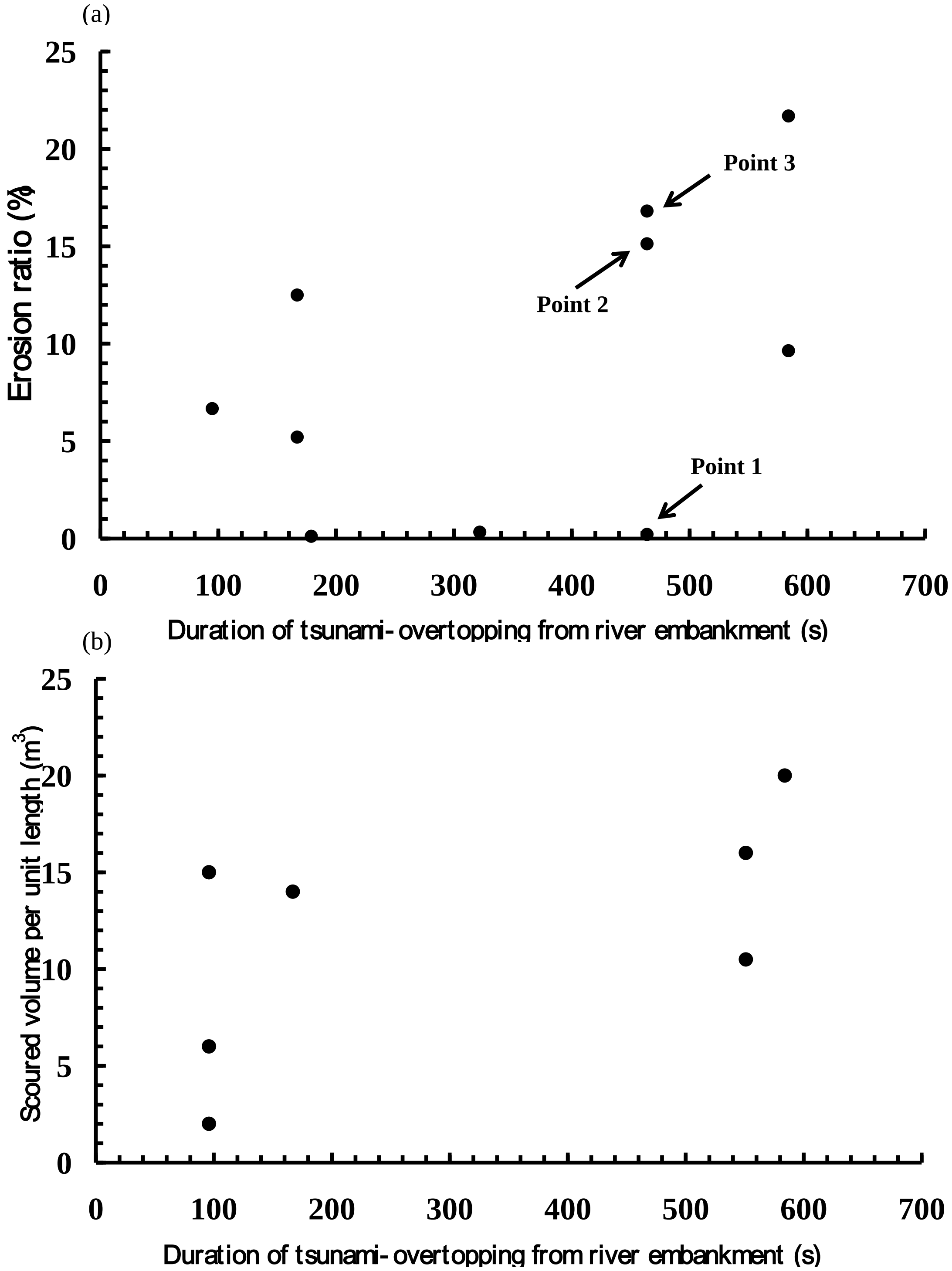

Figure 7: Relationship between overtopping time and (a) erosion ratio and (b) scoured volume. (Locations of Point 1, 2 and 3 are shown in Figure 8. Definition of the parameter in vertical axis is shown in Figure 2.)

Figure 8: The change of Tsunami direction due to the sand bar. Point 1, 2 and 3 are shown the location related to the plots in Figure 7(a). Although a sand bar shown in the aerial photo before tsunami is old, the sand bar existed just before the tsunami came. (Modified the aerial photo provided by Geospatial Information Authority of Japan)

4. Conclusion

The following conclusions and recommendations have been obtained by this study:

1) The flow overtopping river embankments are strengthened on the outer bank side of meandering river sections. The girder of the bridge also increases the overtopping flow depth by the damming of flow propagating in the river. In the right hand side of the Abukumagawa River, severe erosion occurred on the levee slope and hinterlands, and neighboring houses were washed out by the scouring due to the overtopping flow. On contrary, only small erosion was generated at the left hand side of the river, because the tsunami water depth was easily increased there because of the geological condition. The overtopping from river embankment was evaluated to be a submerged overtopping, thus the erosion was not severe.

2) Numerical simulation in Abukumagawa River has reproduced well the tsunami water depth and tsunami overflow depth on the river embankments. On and around the embankment of the Abukumagawa River area, erosion of embankment slope was not so severe when the overtopping time was less than 400 seconds except for the cases where tsunami overtopping flow was strengthened by local geological condition, but over the duration, the erosion amount of embankments depends on the overtopping time. Field investigation also suggests that the erosion was also determined not only by the overtopping time but also by the local river topography and condition, i.e. meandering, sand bar at river mouth, and obstruction by bridge girder.

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