Overflow Pattern and the Formation of Scoured Region by the Tsunami Propagated in River Channels in Great East Japan Earthquake

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Abstract: *The tsunami caused by the Great East Japan Earthquake on 11 March 2011, with a magnitude of 9.0, caused catastrophic damage to people and buildings in the Tohoku and Kanto regions of Japan. A field survey was conducted to elucidate the damage to river embankments and their hinterlands (residential area) by tsunami propagation in river channels and overtopping of embankments. Three, three, and four rivers in Iwate Pref., Miyagi Pref., and the Kanto Region, respectively, were selected for the field investigation. In the hinterlands, the tsunami came from coast and river, and the situation, including the evacuation of people, became complex. Tsunami inundation patterns were classified by the river capacity and whether a river or sea embankment was breached or not. This will provide useful information for making new hazard maps and planning new cities.*

Keywords: *tsunami propagation in river channels, overtopping flow, scoured region, erosion of embankment, meandering of river channel, Great East Japan Earthquake*

1. INTRODUCTION

The Great East Japan Earthquake at 14:46 JST on 11 March 2011 had a magnitude of 9.0 and an epicenter 129 km east of Sendai, and it was followed by a large tsunami that broke many of the sea walls (tsunami gates, large embankments)(Takahashi et al., 2011) and coastal forests (Tanaka, 2012), causing catastrophic damage to people and buildings in the Tohoku and Kanto regions of Japan.

Tsunamis can cause catastrophic damage to both human life and socioeconomic property. Extensive experimental (Peregrine, 1967; Madsen & Mei, 1969) and analytical (Benjamin, 1972) studies have shown that tsunamis are also propagated far upstream in a straight channel of uniform depth and width because a solitary wave like a tsunami propagates without changing its shape and speed. In an actual tsunami, river morphology greatly affects the propagation. 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 as it inundates the inland, and the relationship between the tsunami propagating from the sea and the flow overtopping the banks of a river.

Therefore, the objectives of this study were: 1) to investigate the interactions between a tsunami propagating from the sea and the flow overtopping from a river, 2) to elucidate the effects of river morphology on the tsunami overtopping the embankment, and 3) to determine the effects of inland embankments on tsunami propagation in the hinterlands of the coast or river.
For that objective, field investigations were conducted of three rivers (Heiigawa, Omotogawa and Sakarigawa Rivers) in Iwate Prefecture, three rivers (Abukumagawa, Old and New Kitakamigawa Rivers) in Miyagi Pref., and four rivers (Kujigawa, Nakagawa, Tonegawa, and Mikawa Rivers) in the Kanto Region in April and May 2011. Figure 1 shows the location of the mouth of each river.

Figure 1 Location of investigation sites (locations of the mouth of each investigated river are shown in this figure)

2. SITE LOCATIONS AND MEASUREMENT METHOD

Table 1 shows the river width at the river mouth, tsunami water depth, and height of the sea/river embankment at each investigation site. The tsunami water depth was obtained from "The 2011 Tohoku Earthquake Tsunami

Joint Survey Group" (http://www.coastal.jp/tsunami2011/). As for the tsunami damage, the width of sea/river embankments that were breached and the width/length of the regions that were scoured by overtopping flow are also shown in Table 1.

The tsunami water depth at each site was determined by the height of scars made by collisions of debris with tree trunks or broken branches, water marks, e.g., collision traits, on the walls of damaged houses, marks on broken roofs, or debris located on roofs. The tsunami directions were analyzed by the directions trees and fences were bent and the location of broken houses and scour regions behind embankments or houses. In addition, estimated tsunami water depths of the river or on the embankment and that in the hinterlands were compared to judge the dominant tsunami direction.

Table 1 Characteristics of rivers investigated

Location	Name of River	River width at mouth (m)	Tsunami water depth* (m)	Embankment height		Breach width		Scoured region due to overtopping flow	
				sea embankment (m)	river embankment (m)	sea embankment (m)	river embankment (m)	Width** (m)	Length** (m)
Iwate Pref.	Omotogawa River	200	6.9	9	4	0	230	70.0 - 100.0	14.0 - 15.0
	Heiigawa River	160	8.9	-	3	-	-	-	-
	Sakarigawa River	150	9.3	4	3	0	0	3.5 - 15.0	2.5 - 6.0
Miyagi Pref	New Kitakamigawa Riv	600	7.4	3	3	680	2100	3.0 - 39.0	2.0 - 5.0
	Old Kitakamigawa Rive	200	7.3	4	3	-	0	15.0	4.0
	Abukumagawa River	900	8.8	5	5	260	200	1.5 - 50.0	1.0 - 19.5
Ibaraki Pref.	Kujigawa River	200	4.2	4	4	0	0	-	-
	Nakagawa River	300	3.3	3	3	0	0	-	-
Chiba Pref.	Tonegawa River	700	3.0	5	5	0	0	-	-
	Mikawa River	25	3.4	2	-	0	-	-	-

*Tsunami water depth data were obtained from "The 2011 Tohoku Earthquake Tsunami Joint Survey Group" (http://www.coastal.jp/tsunami2011/)
**The width and length of regions scoured by overtopping flow are shown in Figure 2

3. RESULTS

3.1. Tsunami propagation and overtopping from river embankment (without tsunami gate at river mouth)

The direction and water depths of the tsunami inundation around the Abukumagawa River are shown in Figure 2. At location A, breaching of the sea embankment was observed. Behind the sea embankment, large areas were scoured by the tsunami overtopping of sea embankment. 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 on the embankment. Just downstream, the river embankment was also breached by direct attack of the tsunami. The overtopping from the river to the hinterland was severe at location C, but was a little less severe upstream at locations D and E. However, the overtopping became severe again at location F because it was located on the outer-bank side of the river. 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 condition of houses. The elevation of the road along the river was higher around location F than in locations D and E, so the difference between the ground level of houses and the road was greater. In location D and E, the road in front of houses had a role to prevent erosion, however location D, downward flow still continued and caused erosion. In that case, the overtopping flow caused scoring and local scour around houses that combined to generate large scour area (Figure 3). Thus, houses around location F were completely washed out, not by the tsunami propagated from seaward, but by the tsunami overtopping the river. Similar overtopping from outer bank of a river was also observed in old Kitakamigawa River.

In case of Heiigawa River (Figure 4), a railway bridge which is 1.5 km upstream from the river mouth was washed out after the damming of flow by debris including a ship (Location G). People who temporally escaped on the railway embankment needed to escape far inland by the destruction of the bridge and railway. Most of the tsunami from seaside was stopped at the railway embankment (Location H), but tsunami also propagated by sewage pipe line, inundated in the inland region of the embankment, and overflown from the upstream river embankment when the railway bridge was broken. This case shows that; 1) bridge has some possibility to be a trigger of the overflow from embankment, and 2) tsunami also propagated from sewage line. This should be considered for the tsunami simulation and hazard mapping.

Figure 2 Damaged situation in Abukumagawa River Basin

Figure 3 Large scoured region by overtopping flow (Right hand side of Abukumagawa River)

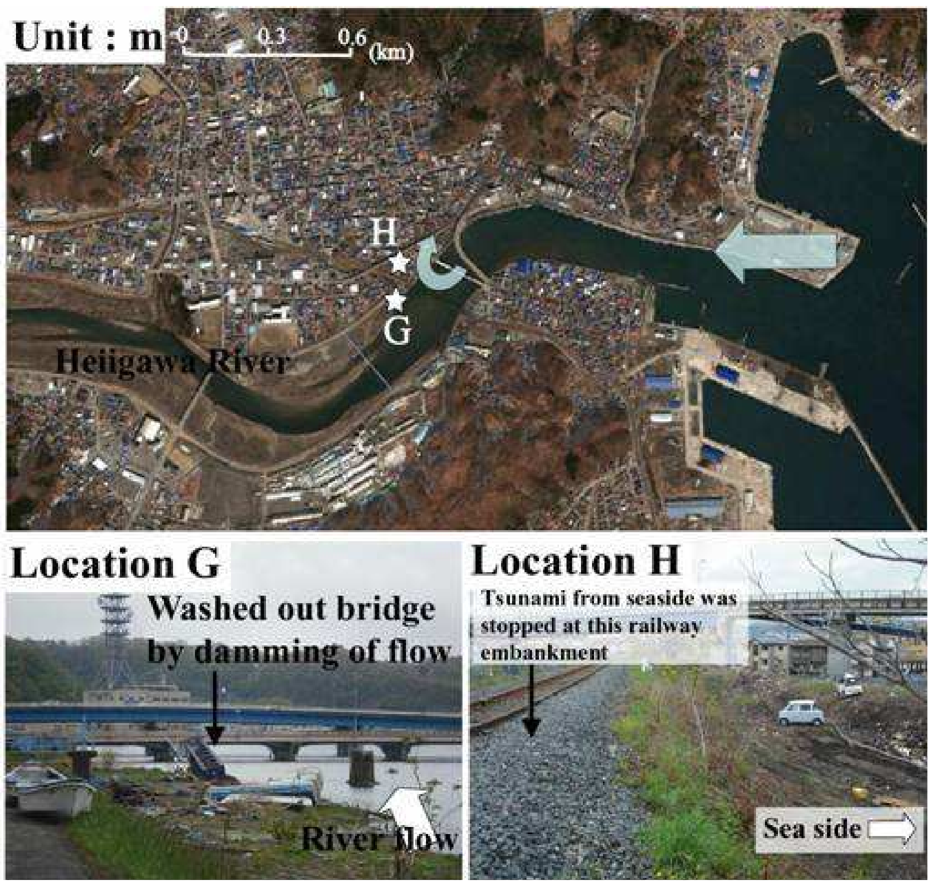

Figure 4 Damaged situation in Heiigawa River Basin

3.2. Change of tsunami propagation pattern with the tsunami gate at river mouth

The Omotogawa River (Figure 5) has a tsunami gate and high sea embankment (around 10 m from the ground on the hinterland side). The overtopping tsunami depth from sea embankment was assumed to around 1.6 m. Many large concrete blocks in front of the sea embankment had been transported by the tsunami, a large scoured region had been generated behind the sea embankment, and the pine trees near the region were overturned (Location I). Most of the houses near the sea and river embankment were washed out by the overtopping flow (Location J). From large scoured regions on floodplain of the river bed, and a scattered region of a broken parapet on the embankment, the breaching was supposed to be occurred from the inland side to the river. Even if a tsunami gate had existed, the tsunami would have been higher than the tsunami gate and the sea embankment; in fact, the tsunami inundation occurred mainly from the high embankment with high potential energy, and washed out or broke the houses. On contrary, in case of a small river in Chiba prefecture, the tsunami was stopped at the gate, because the tsunami height was low in comparison with Iwate Prefecturte.

Figure 5 Damaged situation in Omotogawa River Basin

3.3. Changes of tsunami inundation due presence of road, train embankment, sanitary channel, or mountain

In case of the Sakarigawa River basin (Figure 6), the presence of a road and train embankment changed the direction of most of the tsunami flow intruded from seaward. The tsunami passed through only the culvert of the embankment from seaward to inland, but it continued to overtop the river embankment. Thus, the people who lived upstream of the road and railway embankments received tsunami inundations from two directions. However, in this case, the tsunami overflow from river embankment itself was not large compared with that of the Abukumagawa River. The inland embankment for railway or road is very useful in some cases and needs to be utilized more, considering the tsunami inundation pattern.

In the Kanto Region, the tsunami height was lower than that in the Tohoku area. The Kujigawa, Nakagawa, and Tonegawa Rivers had sufficient capacity to absorb the tsunami. Thus, the areas inundated by the propagated tsunami in the three rivers were restricted. Most of the tsunami intrusions occurred around branches of the river and drainage channels connected to the river. Even when a gate existed between main River and its branches, inundation was also occurred because the earthquake caused a gate trouble by an electricity failure of the system. In the Mikawa River, most of the tsunami was stopped by a sand dune on the coast, but the river itself was open to the sea and a tsunami could easily intrude into and overflow the hinterland from the river. This kind of problem in the gap of an embankment or vegetation barrier was already discussed (Mascarenhas and Jayakumar, 2008; Thuy et al., 2009; Tanaka, 2009, 2011). The river mouth problem is very difficult to mitigate because if a gate is constructed, it may change the tsunami inundation pattern, as in Omotogawa River when the tsunami exceeded the designed gate level.

Figure 6 Damaged situation in Sakarigawa River Basin

4. DISCUSSION

As described in the previous section, overtopping of tsunami from the outer bank side of a river was severe. It is easily assumed from previous studies that the outer bank side is vulnerable to tsunami propagation (Shi et al., 1998; Yuhi et al., 2000). When overtopping occurred here, the scouring of roads in front of houses was not severe, and some houses remained standing although their walls were broken. In contrast, when the difference between the road height and the elevation of the house was large, the scouring became severe and the houses were washed out. The type of utilization of the riverside greatly affects the damage and needs to be studied in more detail in the future.

If a river embankment is not high enough to obstruct a tsunami or a city has rivers or creeks, tsunami inundation occurs not only from the sea but also from the rivers or creeks. In the Old Kitakamigawa River (old channel), or the Sakarigawa River, the tsunami propagated in the river, which is usually faster than a tsunami propagating over land, and the water overflow hit people from two directions.

Many patterns of tsunami propagation in rivers were observed, and they depended on 1) the river capacity (especially embankment height), 2) whether a river or coastal embankment was broken/breached or not, and 3) the existence of an inland embankment or area of high elevation, like a mountain, near the river. For the evacuation from the tsunami, revision of tsunami hazard maps, and new plans for a city design after a tsunami, this complex propagation pattern should be considered and informed to people. The knowledge in this study also needs to be considered in the design of tsunami protection and mitigation systems in a city.

5. SUMMARY

The following conclusions and recommendations were obtained by this study:
1) The flow overtopping embankments occurred mainly on the outer bank side of meandering river sections. Severe erosion occurred on the levee slope, and neighbouring houses were washed out by the scouring due to the overtopping flow.
2) In the hinterlands of coast and river embankment, it is necessary to identify locations where a tsunami can easily overtop for different tsunami conditions, and the information should be utilized for making next hazard map.
3) The tsunami inundation patterns were complex and could be classified based on the river capacity, the existence of gate, and whether a river or sea embankment was breached or not.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Benjamin, T.B. (1972), *The stability of solitary waves*, Proc. R. Soc. Lond. A328, pp.153-183.
Madsen, O.S. and MEI, C.C. (1969), *The transformation of a solitary wave over an uneven bottom*, J. Fluid Mech. 39, pp.781-791.
Mascarenhas, A. and Jayakumar, S. (2008), *An environmental perspective of the post-tsunami scenario along the coast of Tamil Nadu, India: Role of sand dunes and forests*, J. Environmental Management 89, pp.24-34.
Shi, A., Teng, M.H. and Wu, T.Y. (1998), *Propagation of solitary waves through significantly curved shallow water channels*, J. Fluid Mechanics 362, pp.157-176.
Takahashi, S. et al. (2011), *Urgent survey for 2011 Great Japan East Earthquake and tsunami disaster in ports and coasts* (in Japanese with English abstract), Technical Note of the Port and Airport Research Institute, 1231.
Tanaka, N. (2009), *Vegetation bioshields for tsunami mitigation: review of effectiveness, limitations, construction, and sustainable management*, Landscape and Ecological Engineering 5(1), pp.71-79.
Tanaka, N. (2011), *Effectiveness and limitations of vegetation bioshield in coast for tsunami disaster mitigation*, in The Tsunami Threat - Research and Technology, Nils-Axel Mörner (Ed.), ISBN: 978-953-307-552-5, INTECH, Available from: http://www.intechopen.com/articles/show/title/effectiveness-and-limitations-of-vegetation-bioshield-in-coast-for-tsunami-disaster-mitigagation
Tanaka, N. (2012), Effectiveness and limitations of coastal forest in large tsunami: Conditions of Japanese pine trees on coastal sand dunes in tsunami caused by Great East Japan Earthquake, Annual Journal of Hydraulic Engineering, JSCE, Vol.56, (in press).
The 2011 Tohoku Earthquake Tsunami Joint Survey Group" (http://www.coastal.jp/tsunami2011/)
Thuy, N.B., Tanimoto, K., Tanaka, N., Harada, K. and Iimura, K. (2009), *Effect of open gap in coastal forest on tsunami run-up - Investigations by experiment and numerical simulation*, Ocean Engineering 36, pp.1258-1269.
Yuhi, M., Ishida, H. and Mase, H. (2000), *Numerical study of solitary wave propagation in curved channels, Coastal Engineering 2000, Proceedings of the Conference, American Society of Civil Engineers*, Sydney, Australia.