Field measurements and numerical modeling for the run-up heights and inundation distances of the 2011 Tohoku-oki tsunami at Sendai Plain, Japan

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We conducted an urgent field survey at the Sendai Plain to measure the run-up heights and inundation distances of the 2011 Tohoku-oki tsunami. We used GPS measurements because of the remarkably long inundation distances (ca. 5.4 km). We established an accurate measurement scheme using the far electric reference points (about 350 km). Using this method, we quickly measured 69 run-up heights within 3 days. The tsunami run-up heights and inundation distances varied mainly according to the local topography, ranging from 9.6 m at 0.4 km to 0.2 m at 5.4 km, respectively. Furthermore, artificial structures and topography played an important role in constraining the inundation limit. Our observations are important for future analyses using aerial and satellite imagery and numerical modeling in the area because the maximum inundation area might be underestimated in the images as a result of the subtle traces of the tsunami inundation, which were difficult to identify in the field. However, results show that numerical modeling might not reproduce minor inundation beyond the highway without sufficiently high-resolution topographic data because data for the modeling are usually rough, and the highway, small channels, and street gutters, which played an important role in local inundation, are too small a resolution to be recognized in the model.

Key words: The 2011 Tohoku-oki tsunami, run-up height, Sendai Plain.

1. Introduction

An earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku, Japan on March 11, 2011 (e.g. Hirose *et al.*, 2011). Soon thereafter, a large tsunami (designated hereinafter as the 2011 Tohoku-oki tsunami) struck the Pacific coast of eastern Japan (e.g. Fujii *et al.*, 2011; Hayashi *et al.*, 2011; Maeda *et al.*, 2011; Mori *et al.*, 2011). After late March, the joint survey group conducted many field surveys to measure the run-up height, flow depth (= inundation depth), and inundation area of the tsunami along the Pacific coast of eastern Japan. More than 5,000 data points have been collected (The 2011 Tohoku Earthquake Tsunami Joint Survey Group (TETJSG), 2011). Such extensive research clarified that the maximum run-up height of the tsunami (ca. 40 m) is the largest value among all Japanese recorded tsunami that have been documented during its history (TETJSG, 2011).

The 2011 Tohoku-oki tsunami is also characterized by its remarkably long inundation distance, especially at the

Sendai Plain (Fig. 1). In fact, tsunami inundation of up to 5 km was observed soon after the tsunami based on analyses of aerial photographs and satellite images (e.g. Geospatial Information Authority of Japan (GSI), 2011). Given such a great inundation distance, several difficulties exist for measuring the run-up heights during the field survey soon after the tsunami because: (1) the tsunami traces are subtle near the inundation limit because of sufficient decay of the tsunami energy and an urgent field survey is necessary before such subtle traces disappear, but (2) it is technically difficult to measure many run-up height data quickly using standard measurement methods by levels or total stations because such measurements take a long time for quantitative data collection.

To overcome these problems, we conducted an urgent field survey in early April, 2011, particularly addressing the measurement of the run-up heights along the Sendai Plain using GPS measurement instruments under the organization of the Joint Survey Group. This report describes our survey results of the run-up heights and discusses variation of the run-up heights in relation to the local topography. We also tested whether numerical modeling for the tsunami inundation can reproduce the ground truth.

Fig. 1. Measured and modeled run up heights (m) and inundation distances (km) at the studied area. IA: inundation area.

2. Study Area

The Sendai Plain, in a broad sense, has a 50-km stretch of coastline, which extends from Sendai city at the northern margin to Yamamoto town at the southern margin (Fig. 1). The plain is segmentalized into northern, central, and southern parts, by the Natori and Abukuma rivers. The plain reaches its maximum width of 10 km in the central part, which is bordered by Abukuma and Natori rivers. The width of the plain becomes narrow toward its southern margin. The elevation along the west margin of the plain is between 5 and 10 m, although most of the plain is less than 5 m in elevation. The inclination of the plain becomes steep in the southward part closer to the ocean.

The natural parts of the plain, which has a marine and fluvial origin during the last 25,000 years, are characterized by beach ridges, back marshes, and natural levees. The beach ridges are actually sand dunes, which have developed parallel to the present coastline and paleo-coastlines (Matsumoto, 1985), and which have slightly higher elevation than surrounding areas. Formed by sea-level fluctuations during the late Holocene, the beach ridges have four recognizable rows. Each is numbered as I, I', II, and III from the inland to the coast (Matsumoto, 1984). In the southern part of the plain, the beach ridges are better developed, and the width of each beach ridge is wider than the northern part (Ito, 2006). In addition, the beach ridges have higher elevations in the southern Sendai Plain than in the northern part. The formation ages of beach ridges I, I', II, and III have been dated respectively at 5,000–4,500 yr

BP, 3,100–3,000 yr BP, 2,800–1,600 yr BP, and newer than 1,000–700 yr BP. The average rate of seaward migration of the coastline was estimated at 0.6 m/yr in the northern part and 1.2 m/yr in the southern part during the last 5,000 years (Ito, 2006). The back marshes, including trace lagoons, developed in the lowlands between and behind the beach ridges in the plain. Natural levees formed along the old river channels. They were formed and remain because of the meandering of the two rivers.

A northward-directed coastal current is dominant in Sendai Bay. The main source of beach material is sediment that originated from the Abukuma and Natori rivers, and partly from the cliff coasts of Joban Coast further south. At present, sediment transport by the coastal current is segmentalized by guide walls that have been constructed at the river mouths and fishery harbors. Because of modern development of dams in the upstream of each river and these coastal structures, significant regression and progression of the coastline, which reaches around several meters per year, has been observed during the last 20 years (Tohoku Regional Bureau, 2000).

In general, the study area includes the beach, with up to 4 m high coastal dune ridges covered with pine forest and low-lying rice paddy fields at sea level. Offshore and on-shore wave breakers (5.2–7.2 m in height for onshore wave breaker) were settled in several places for maintaining the beach sand and to protect it from storm wave impact. The Sendai Tobu Highway, the embankment of which is approximately 10 m high, runs north-south at approximately 2.5–

Fig. 2. (a) Computational domain for the model of tsunami propagation and run-up to Sendai Plain and ultimate sea-bottom deformation as a wave source of the Tohoku-oki tsunami (Imamura *et al.*, 2011). The distribution of the sea-bottom deformation was calculated based on Okada (1985). (b) Modeled flow depth (m) over the study area.

4.5 km from the shoreline (Fig. 1). The highway embankments have intermittent underpasses.

3. Methods

3.1 Field measurements

Field surveys were conducted during April 2–4, 2011, the earliest timing to conduct the survey after rescue efforts and life safety issues had been resolved to most of the tsunami-affected area residents. Figure 1 portrays the survey area at the Sendai Plain from Tagajo to Yamamoto, extending 40 km north-south. Based on the field investigation, we first identified the inundation limits based on the tsunami traces and estimated the approximate inundation distances perpendicular to the shoreline. Then we measured the absolute elevations (run-up heights) at 69 points using GPS measurement instruments (Promark 3; Ashtech) of average 0.5–2 km interval. Basis of the elevation data is Tokyo Peil (T.P.).

For measuring the absolute elevations at the Sendai Plain using GPS instruments, it is noteworthy that the adjacent electric reference points (GPS base station) were also moved by crustal deformation of the earthquake on March 11, 2011. In fact, the electric measurement point at Yamato, 30 km northeast from Sendai, was displaced horizontally approx. 4 m eastward and subsided approx. 50 cm. Moreover, they were shut down until April 8, 2011. Therefore, it was necessary to refer the electric reference points that were distant from the affected area, where crustal displace-

ment was minimal. To do so, we set a Proflex 500 as the base site, which can refer to electric points within 500 km, at the roof of the highest building at Tohoku University (approx. 160 m higher than T.P.) and referenced the electric reference points at Matsumae in Hokkaido prefecture and Gotenba in Shizuoka prefecture (approx. 350 km from Sendai) (Fig. 1). At these electric reference points, no significant vertical crustal movement was recorded. Therefore, run-up heights can be measured accurately.

However, approx. 20 cm horizontal movement occurred at the Matsumae and Gotenba electric reference points. Nevertheless, considering that the major objective of this research is the highly accurate measurement of run-up heights, we neglected the effects of the horizontal crustal movements because the movements were less than the error to determine the tsunami inundation limit during the field survey, which should have error of less than a few meters.

The GPS rovers (Promark3) in the field were set at the inundation limit and measured up to the observation ranges from the location of the base site of the Proflex500. It took approximately 5–20 min to measure a single point, depending on the satellite condition. Based on this scheme, we were able to measure the run-up heights promptly and accurately (approx. ± 20 cm error for elevation).

3.2 Numerical modeling

To simulate the tsunami propagation in the open sea, we used a nonlinear equation to describe a shallow-water wave and to simulate tsunami propagation in the coastal zone

Table 1. Field measurement data at all points. All data represent the run-up heights (m).

no	City/town	Latitude	Longitude	Height (m)	Distance (km)	Note
1	Natori	38.192	140.931	1.30	3.4	straw in the paddy field
2	Natori	38.191	140.928	1.04	3.5	straw in the paddy field
3	Natori	38.190	140.926	1.54	3.8	straw in the paddy field
4	Natori	38.189	140.927	1.53	3.6	straw in the paddy field
5	Natori	38.179	140.920	1.34	3.7	straw in the paddy field
6	Natori	38.183	140.923	1.55	3.7	straw in the paddy field
7	Sendai	38.209	140.934	2.20	3.6	straw on the road
8	Sendai	38.213	140.936	1.67	3.7	straw in the paddy field
9	Sendai	38.229	140.943	2.39	3.9	straw in the paddy field
10	Sendai	38.224	140.943	2.25	3.7	straw in the paddy field
11	Sendai	38.220	140.941	2.08	3.6	straw in the paddy field
12	Sendai	38.218	140.940	1.85	3.6	straw on the road
13	Sendai	38.218	140.937	2.30	3.8	straw on the bridge
14	Sendai	38.232	140.944	2.25	4.0	straw in the paddy field
15	Sendai	38.232	140.945	2.38	4.0	straw in the paddy field
16	Sendai	38.233	140.945	2.22	4.0	straw in the paddy field
17	Sendai	38.234	140.946	2.36	4.0	straw in the paddy field
18	Sendai	38.233	140.950	2.06	3.7	straw in the paddy field
19	Sendai	38.234	140.951	2.14	3.7	straw in the paddy field
20	Sendai	38.233	140.952	2.01	3.5	straw in the paddy field
21	Sendai	38.236	140.951	1.94	3.7	straw in the paddy field
22	Tagajo	38.285	140.987	2.61	1.6	eye witness account
23	Tagajo	38.288	140.999	3.42	1.7	straw on the stair
24	Tagajo	38.292	141.015	3.02	1.6	watermark
25	Tagajo	38.294	141.016	1.92	1.6	watermark
26	Shichigahama	38.290	141.044	3.90	1.4	debris on the road
27	Shichigahama	38.280	141.051	4.40	0.1	debris on the road
28	Shichigahama	38.280	141.048	6.92	0.1	debris on the road
29	Shichigahama	38.291	141.046	3.23	1.4	debris on the road
30	Natori	38.161	140.905	1.88	4.1	sediment
31	Natori	38.159	140.901	1.92	4.4	straw in the paddy field
32	Natori	38.156	140.898	2.21	4.5	straw in the paddy field
33	Natori	38.155	140.894	1.25	4.8	straw in the paddy field
34	Natori	38.155	140.891	2.18	5.1	straw in the paddy field
35	Natori	38.152	140.889	2.00	5.1	straw in the paddy field
36	Natori	38.150	140.887	0.93	5.2	straw in the paddy field
37	Natori	38.143	140.884	0.81	5.2	straw in the paddy field
38	Natori	38.141	140.882	2.15	5.4	straw in the paddy field
39	Natori	38.138	140.883	1.05	5.2	straw in the paddy field
40	Natori	38.131	140.883	0.26	4.9	straw in the paddy field
41	Natori	38.128	140.883	1.09	4.9	straw in the paddy field
42	Natori	38.113	140.881	2.77	4.6	straw in the paddy field
43	Iwanuma	38.097	140.894	2.01	3.1	straw in the paddy field
44	Watari	38.081	140.888	1.21	3.3	straw in the paddy field
45	Watari	38.067	140.882	1.30	3.7	straw in the paddy field
46	Watari	38.062	140.878	1.07	4.0	straw in the paddy field
47	Watari	38.050	140.873	1.10	4.4	straw in the paddy field
48	Shichigahama	38.307	141.068	3.86	1.4	straw in the paddy field
49	Yamamoto	37.908	140.901	9.05	2.0	debris
50	Yamamoto	37.903	140.915	7.61	0.4	debris
51	Yamamoto	37.910	140.912	9.60	1.1	debris
52	Yamamoto	37.923	140.907	9.44	1.3	debris
53	Watari	38.040	140.873	1.46	4.2	watermark
54	Watari	38.040	140.870	1.36	4.5	watermark
55	Watari	38.033	140.874	1.66	4.0	watermark
56	Watari	38.028	140.870	1.30	4.3	straw in the paddy field
57	Watari	38.020	140.871	1.76	4.1	straw in the paddy field
58	Watari	38.009	140.872	1.77	3.9	debris
59	Yamamoto	37.927	140.898	5.00	2.1	debris
60	Yamamoto	37.933	140.897	8.49	2.0	debris

Table 1. (continued).

no	City/town	Latitude	Longitude	Height (m)	Distance (km)	Note
61	Yamamoto	37.939	140.896	7.75	2.0	debris
62	Yamamoto	37.945	140.899	5.07	1.7	debris
63	Yamamoto	37.962	140.886	5.72	2.7	straw in the paddy field
64	Yamamoto	37.956	140.887	4.52	2.6	straw in the paddy field
65	Yamamoto	37.953	140.893	8.32	2.1	straw in the paddy field
66	Yamamoto	37.975	140.884	2.27	2.7	straw in the paddy field
67	Yamamoto	37.984	140.876	2.22	3.5	straw in the paddy field
68	Yamamoto	37.994	140.877	1.66	3.4	straw in the paddy field
69	Yamamoto	38.004	140.877	1.61	3.4	straw in the paddy field

and inundation on land using a Cartesian coordinate system (Goto *et al.*, 1997), with allowance made for variable bottom friction (Kotani *et al.*, 1998; Kaiser *et al.*, 2011). The governing equations are described as follows.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left(\frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left(\frac{MN}{D} \right) \\ + gD \frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} M \sqrt{M^2 + N^2} = 0 \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left(\frac{MN}{D} \right) + \frac{\partial}{\partial y} \left(\frac{N^2}{D} \right) \\ + gD \frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/3}} N \sqrt{M^2 + N^2} = 0. \end{aligned} \quad (3)$$

In those equations, η is the elevation of the water surface from the still water level, M and N respectively denote discharge fluxes in the x -direction and y -direction, D signifies the total water depth ($= h + \eta$), and n represents Manning's roughness. The staggered leap-frog method, a finite-difference method, was used to solve equations numerically (Goto *et al.*, 1997). The roughness coefficient at each grid cell is set according to the land condition based on findings by Kotani *et al.* (1998) and Kaiser *et al.* (2011). In this study, a roughness coefficient of 0.025 was assigned for water, 0.03 for bare ground and grassland, 0.04 for control forest and 0.05 for residential area.

We assumed a composite fault model proposed by Imamura *et al.* (2011) as the source for the tsunami (Fig. 2(a)). Although this model is a tentative one, it reproduces the tidal record well, in addition to the measured run-up height and local subsidence at the Pacific coast of Japan (Imamura *et al.*, 2011). We constructed a nested grid system across a wide area (regions 1–3) to the study area (region 4) (Fig. 2(a)). Spatial grid sizes of respective regions were 1,215 m for region 1, 405 m for region 2, 135 m for region 3, and 45 m for region 4. The calculation time is 180 min after the tsunami generation. The numerical modeling used public bathymetric and topographic datasets provided by the Central Disaster Prevention Council, Japan, and the Tohoku Regional Bureau, Ministry of Land, Infrastructure and Transport. The Sendai Tobu Highway is not well incorporated in the topographic data in region 4 because it is not reproducible in the 45 m grid size.

4. Results

Tsunami inundation in the Sendai Plain is generally classified into areas of three types from north to south (Fig. 1, Table 1): (1) inundation in the urban city at the Tagajo and Shichigahama near the Sendai Port (area 1); (2) inundation in the very wide and flat plain at Sendai, Natori, Iwanuma, and Watari plus north of Yamamoto (area 2), and (3) inundation in the narrow plain at Yamamoto (area 3).

4.1 Area 1

Tagajo and Shichigahama are located north of the Sendai megacity close to the Sendai Port (Fig. 1). The area is densely populated. Therefore, the tsunami inundation process was very complex because artificial objects such as buildings, infrastructure, and port functions affected the tsunami inundation. Most tsunami traces at the inundation limit were marked by watermarks on the buildings (Fig. 3(a)) and concentrations of small debris. The run-up heights and inundation distances in the densely populated area were, respectively, 2–4 m and 1.4–1.7 km (Fig. 1). However, the run-up height and inundation distance were up to 6.9 m and 0.1 km, respectively at places where a steep slope was located behind the small port (Fig. 3(b)).

4.2 Area 2

At most places in this area, tsunami damage was extremely severe near the coastal zone. In fact, houses and coastal trees were destroyed extensively and much debris was deposited elsewhere (Fig. 4(a)). According to the TETJSG (2011), tsunami flow heights (inundation heights) near the coastal zone in this area were ca. 15 m.

The tsunami flow depths decrease continuously landward to nearly 0 m (e.g. Goto *et al.*, 2011a). The Sendai Tobu Highway played an important role in protecting the area from further tsunami inundation, especially from Sendai to Iwanuma, where the highway is located up to 4.5 km from the shoreline (e.g. Sugawara *et al.*, 2012). In fact, much floating debris was stopped at the eastern (seaward) side of the highway because of the 10-m high embankment (Fig. 5(a)). Although major tsunami inundation generally stopped at the highway from Sendai to Iwanuma, tsunami inundation reached far beyond the highway at Watari, where the highway was located up to 2.5 km from the shoreline. Moreover, even in the Sendai to Iwanuma area, the tsunami inundation was not fully halted at the highway because elevated bridges and drainage channels allowed the tsunami to flow underneath the highway (Fig. 5(b)). Consequently, the tsunami inundated up to 5.4 km further west from the highway from the shoreline (Figs. 6(a), 7).

Fig. 3. (a) Watermark on the wall of building at Tagajo (no. 24 in Table 1). (b) Tsunami traces at the inundation limit at Shichigahama (no. 27).

Fig. 4. (a) Much debris deposited close to the coastal zone near the Teizan canal of approximately 0.4 km from the shoreline at Arahama area in Sendai. (b) Tsunami traces at the inundation limit at Sendai (no. 8). (c) Tsunami inundated further inland through the street gutter (no. 8).

Beyond the highway, tsunami traces are subtle and mostly characterized by the concentration of paddy straw and light debris (Fig. 4(b)). No severe damage was observed near the inundation limit. It was also observed that the paddy straw was deposited close to the artificial channels and street gutters (Fig. 4(c)). This observation suggests that the tsunami inundation extended further inland

through such low water passages. The tsunami inundation sometimes stopped in front of local undulations such as rice paddy dykes.

Run-up heights in this area were almost identical, as high as ca. 3 m, whereas inundation distances were 3.1–5.4 km (Fig. 1).

Fig. 5. (a) Seaward (east) side of the Sendai Tobu Highway at Sendai. The embankment is 10 m high. Much debris was deposited in front of it. (b) Bridge of the highway. Tsunami could have flowed through such an underpass further inland.

Fig. 6. Aerial photographs taken at (a) Sendai to Natori close to the Natori River and (b) near Sakamoto Station in Yamamoto (provided by Asia Air Survey Co. Ltd.). Both photographs were taken on March 13, 2011. Numbers on the photo correspond to those in Table 1.

4.3 Area 3

Different from the flat and wide plain in area 2, area 3 is characterized by the narrower and steep plain. The inundation limit is generally at the bottom of the hill (Fig. 6(b)), probably because the plain is narrow and because tsunami inundation was forced to stop at the steep slope of the hill. Moreover, the inundation limit line was observed clearly because of the concentration of much large floating de-

bris even at the inundation limit (Fig. 8). Tsunami run-up heights and inundation distances are, respectively, highly variable: 9.6 m at 0.4 km to 1.6 m at 3.5 km.

4.4 Modeled run-up heights and inundation distances

Figure 2(b) shows the modeled maximum flow depth over the study area. The figure shows maximum flow depths near the shoreline as nearly 10 m, which are consistent with the measured values (TETJSG, 2011). The figure shows

Fig. 7. Measured and modeled tsunami inundation distance and run-up heights (m) shown on the 5 m DEM data before the tsunami. IA, inundation area.

Fig. 8. Inundation limits at (a) no. 60 and (b) no. 52. The clear limit lines are notably different from around Sendai (Fig. 4(b)).

further that the narrower plain at the south of the Sendai Plain was fully inundated but a wider plain area was characterized by partial inundation up to 6 km. In addition, Fig. 1 shows modeled run-up heights and inundation distances over the study area. Overall, the modeled run-up

heights and inundation distances are consistent with the measured ones, especially in areas 1 and 3. However, the modeled run-up heights and inundation distances are over-estimated for area 2.

Fig. 9. Topographic profiles along transects A and M in Fig. 1 (modified after Abe *et al.*, 2011; Goto *et al.*, 2011b). CF, coastal forest; RP, rice paddy.

Fig. 10. Measured inundation distance (km) vs. run-up heights (m) at the studied sites.

5. Discussion

The tsunami inundation process at the Sendai Plain is generally controlled both by the local topography and by land use. Figure 9 presents a comparison of the cross-sectional topographic profiles along transects in Sendai in area 2 (Transect A) and in Yamamoto in area 3 (Transect M)

(see Fig. 1 for locations) as measured by Abe *et al.* (2011) and Goto *et al.* (2011b). Along transect A in Sendai, the topography is characterized by the remarkably flat surface behind the sand dune (Fig. 9(a)), although it is characterized by steep topography along transect M in Yamamoto (Fig. 9(b)).

In area 2, the inundation limit is also affected by the local topography as portrayed in Fig. 7, which shows that the tsunami waves generally stopped at around 2–3 m high elevation. In area 2, the tsunami traces near the inundation limit line were subtle and were sometimes difficult to identify even a few weeks after the tsunami, probably because the tsunami flow was weak and insufficient to transport large debris; only paddy straw and light debris were transported and deposited around the limit line.

In contrast, the topography in area 3 is characterized by steep slope inclination (0.3%, Abe *et al.*, 2011). In this area, large debris was deposited to a noticeable degree, even at the inundation limit (Fig. 8) and tsunami flow might have been forced to stop in front of the topographic high.

In addition to the topography, land use is important to control the inundation limit. In fact, the inundation limit at area 1 was complex because buildings and infrastructure as well as the rivers affected the tsunami inundation process. Moreover, the Sendai Tobu Highway played an important role in determining the inundation limit line, which in turn suggests that the highway partly acted as protection against the tsunami inundation (Sugawara *et al.*, 2012).

A negative correlation exists between the inundation distances and run-up heights (Fig. 10) probably because both are mainly controlled by the topography. The inundation distance was short and the run-up height was high at the steep topographic setting, although they were long and low in the flat plain area. It is important to note that area 1 (densely populated area) was characterized by a lower run-up height and shorter inundation distance than in other areas (Fig. 10), probably because the artificial objects reduced the tsunami energy. Consequently, tsunami inundation was stopped at the place with lower height and shorter distance from the shoreline.

The numerical calculation generally reproduced the overall trend of the measured run-up heights and inundation area well at areas 1 and 3 (Fig. 1), probably because the run-up heights and inundation area in these areas are generally controlled by the local topography. However, these are generally overestimated in numerical calculations in area 2, probably because the spatial grid size (45 m) is insufficient to reproduce the local land use, especially the Sendai Tobu Highway, which is expected to have acted to reduce the tsunami energy greatly.

6. Conclusions and Implications for Future Analyses

One important result of our study is that we established a scheme of quick and accurate measurement of the run-up heights at the remarkably long tsunami inundation area using GPS instruments. By adopting this scheme, we were able to measure an average of 23 points each day, while standard measurement methods (e.g., leveling and total station), which measure the elevation from the shoreline, might have limited measurements to only 1–2 points per day with larger error than our measurements. Considering that the subtle tsunami traces at the inundation limits disappeared quickly (even in early April, traces are not recognizable at few places), our measurement scheme of the run-up heights is expected to be effective.

The results showed extensively long inundations (ca. 5.4 km) and low run-up heights (ca. 3 m) at the wide and flat plain in area 2, and highly diverse run-up heights and inundation distances at area 3. In urban area 1, tsunami inundation is more complex. Both topography and land-use conditions affect the run-up heights and inundation distances. A large difference of the tsunami traces exists at the inundation limit along the long inundation/low run-up height area (area 2) and short inundation/high run-up height area (areas 1 and 3). The former is characterized by subtle traces such as the minor redistribution of paddy straw, whereas the latter is characterized by the concentration of much floating debris.

Our observations at Sendai Plain can be regarded as an important ground truth for interpreting the results of future analyses using aerial/satellite imageries and numerical modeling. In fact, interpretation of aerial and satellite imageries might underestimate the maximum inundation area, especially at area 2, because the subtle traces of the tsunami inundation were difficult to identify even in the field. However, numerical modeling cannot reproduce the minor inundation from the highway because the topographic data for the modeling are usually rough. Moreover, the small channels and street gutters, which played an important role in local inundation beyond the highway, are not reproducible in the modeling without meter-scale high resolution topographic data.

Our study is critically important to elucidate the limitations of analyses of aerial/satellite images and numerical modeling to elucidate the inundation process of a remarkably flat and wide plain, as with the Sendai Plain.

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