THE ROLE OF URBAN DEVELOPMENT PATTERNS IN MITIGATING THE EFFECTS OF TSUNAMI RUN-UP

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ABSTRACT: This study seeks to understand the relationship between urban development patterns and the extent of physical damage caused by widespread tsunami run-up. The project had four major objectives: 1) to perform field studies to collect perishable data on coastal community performance following the 2011 Tohoku earthquake, 2) to develop an understanding of the "data landscape" in post-earthquake Japan, 3) to quantify the effect of user experience in interpreting remotely-sensed images on the accuracy of post-event damage assessments, and 4) to develop a preliminary understanding of the role that urban development patterns played in either mitigating or exacerbating tsunami-induced impacts.

Key Words: Tsunami, damage, urban development patterns, mitigation, GIS, remote sensing

INTRODUCTION

This NSF-sponsored RAPID grant study (in association with a J-RAPID grant awarded to the third and fourth authors of this paper) sought to understand the relationship between urban development patterns and the extent of physical damage caused by widespread tsunami run-up. The 11 March 2011 Tohoku, Japan earthquake caused significant damage all along the northeastern coast of Japan, with almost all of it resulting from tsunami waves that reached heights in excess of 20 meters. In order to understand how the built environment can affect the performance of communities in a tsunami, we studied eleven communities in the Miyagi/Chiba/Ibaraki Prefectures – areas ranging from minor to moderate damage to complete devastation. Our central research question was: Can the *urban topology* of a community mitigate the effects of a tsunami by isolating the more damaging surge effects to a few well-designed and well-placed buildings, thus limiting damage to "protected" buildings to just rising water effects?

Previous research on the 2004 Indian Ocean earthquake and tsunami (Chang et al., 2006) clearly showed that the presence of healthy natural ecosystems can indeed impede the progress of strong wave fronts, thus limiting damage to rural coastal communities. We designed our investigation of the built environment to explore if there were similar benefits to urban communities by examining data from the Tohoku earthquake.

Knowing the answer to the question above could have significant ramifications: Reconstruction can incorporate either higher design standards for buildings or specific neighborhood configurations that may serve as a first or second line of defense in future events; knowing that particular buildings will be safer because of the type of construction and where they are located relative to other buildings may provide important evacuation points for residents that cannot quickly escape from an area (conditions that may be exacerbated because of traffic concerns); and data and observations from this event will help to inform future vulnerability models especially ones that consider the impact on small and moderate-sized communities. For example, classifying towns or communities by vulnerability grade based on projected tsunami heights and community configurations would be an improvement over current standards, such as those that focus primarily on the performance of individual buildings (FEMA, 2008).

POST-EVENT SURVEYS

Approximately four months after the March 2011 event, the ImageCat team along with Professor Shunichi Koshimura of Tohoku University and Professor Fumio Yamazaki of Chiba University, performed ground surveys of those areas affected by the tsunami. The survey lasted six days and included 11 communities which spanned from Chiba (in the south) to Miyako (in the north). These communities ranged from small fishing villages to moderately large industrial ports. The goal was to select a range of communities that would help understand what factors led to extreme vulnerability to tsunami effects, and what factors led to strong resistance. As part of this survey, approximately 1000 GPS-stamped photos were taken and several hours of video were captured. The communities studied include: Ishinomaki, Kamaishi, Kesennuma, Matsushima, Minamisanriku, Miyako, Ofunato, Onagawa, Otsuchi, Rikuzentakata, Sendai and Yamada. A sample of the extent of the survey and GPS routes is shown in Fig. 1.

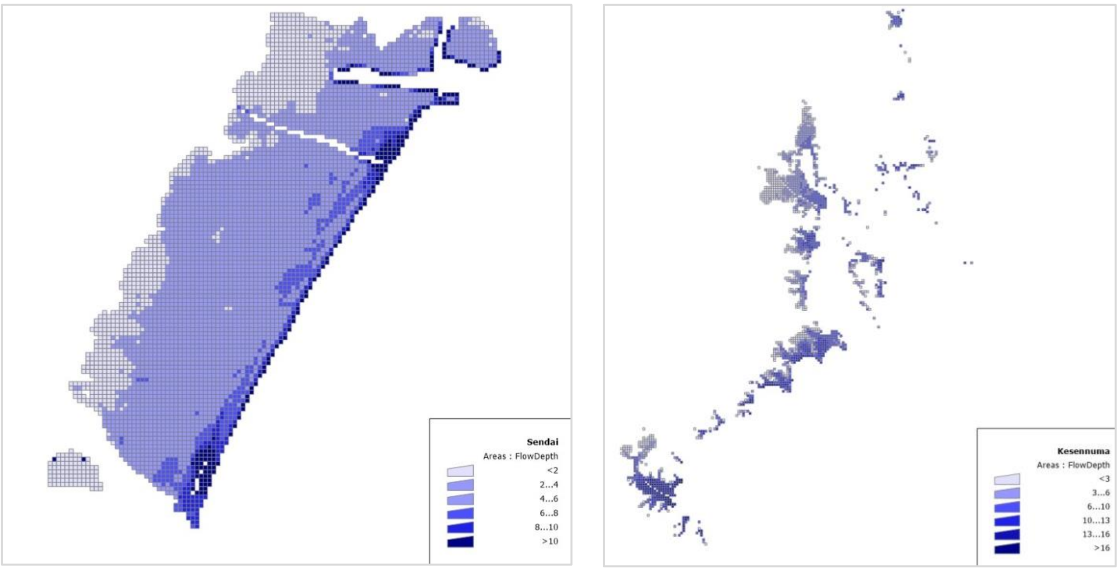
Fig. 1 Sample City Route and GPS Trail

DESCRIPTION OF DATA

In addition to ground survey datasets captured by the ImageCat team, aggregated datasets for the eleven study areas was provided to the project team by several Japanese collaborators including Professor Shunichi Koshimura and Professor Fumio Yamazaki. The original data source is attributed to the survey results of the Japanese Government, City Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), published in March of 2012. Ground surveys conducted after the earthquake resulted in detailed building summaries, a comprehensive inventory of building characteristics, local flood depths and social impacts on a regional level for all areas affected by the tsunami. All building data was provided in a GIS format (.shp) with metadata attached in an Excel spreadsheet. Several sites include ground survey photographs taken at the time of the survey. The following subsections describe in detail the different datasets used in this benchmarking study.

GIS Data

Information regarding maximum flow depth was presented as aggregate data in a 100 x 100 m grid cell system. To assign flow depths to structures, the centroid of each building was first extracted to prevent assigning multiple flow depths to the same polygon. The 100m grid was then overlaid with the building centroid data layer and the corresponding flow depth was then assigned to the structure. Fig. 2 below shows grid maps for sample cities Sendai and Kesennuma with maximum flow depths on a grid cell basis. Flow depths for Sendai reached 10 meters; for Kesennuma, flow depths reached as high as 16 meters.



Sendai **Kesennuma**

Fig. 2 Maps showing Maximum Flow Depths in meters in Sendai and Kesennuma

Buildings Database

The MLIT GIS database provided building footprints and associated data for each structure. Each record is assigned a unique ID that links the polygon (building footprint) to the detailed building summary. The following information (if recorded during the field survey) is available for each building footprint: occupancy class, structural type, tsunami flow depth (m) assigned from the grid (explained in the previous section), number of stories, and an assigned damage state. Building footprint area (square meters) was not included, however this information could be extracted from the building footprint polygon and assigned back to the structure to include in the database. Fig. 3 shows the building footprints for the city of Sendai.

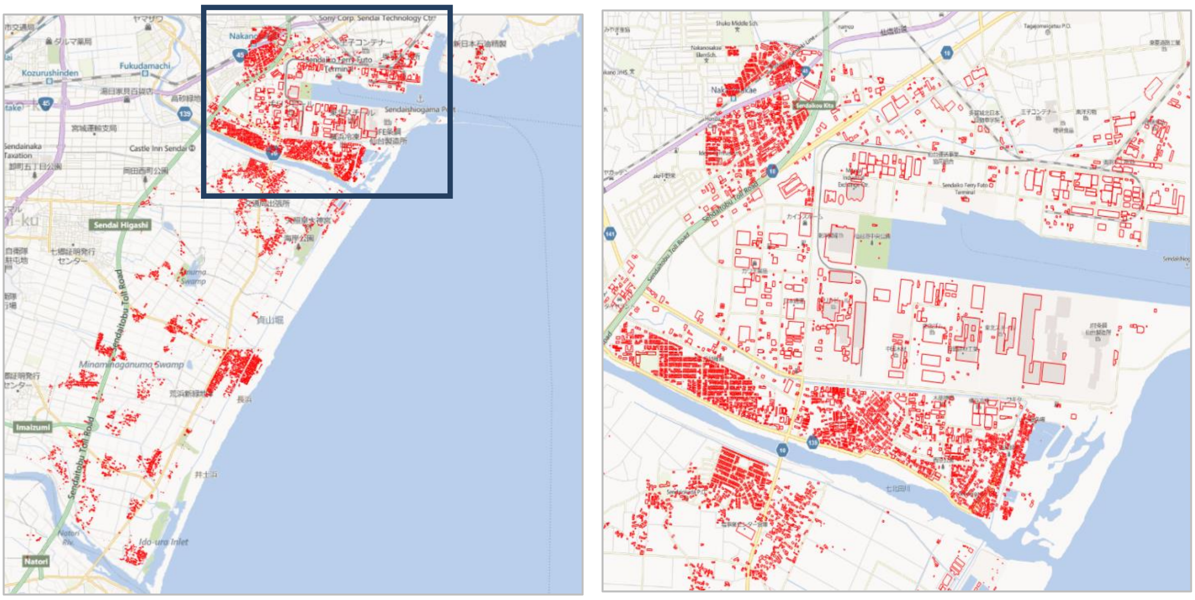


Fig. 3 Building Footprints for Sendai extent (left) and Sendai Port (right)

ANALYSIS

After studying the eleven communities affected by the tsunami, we discovered several important lessons that should influence our understanding of community resilience to tsunami effects. First, we determined there is a statistically significant trend between damage ratios (number of buildings destroyed over total number of buildings) and flood depth or inundation height. This trend was not unexpected; significant damage ratios (over 50%) generally occurred at flood depths of 2 to 4 meters or higher. A majority of structures within the subject communities were built using traditional wood-framed construction, which can account for the higher damage ratios at the lower flood depths. Results from the eleven communities can be found in Table 1.

Of the eleven communities studied, the team identified three which had an urban/industrial barrier we believe helped protect the residential areas directly behind these areas. These large coastal buildings consisted of either reinforced-concrete commercial/residential structures, steel warehouses to accommodate the industrial/fishing communities or a combination of both. It should be noted all eleven communities had some type of tsunami protection in the form of either manmade (tsunami walls and breakwater) or natural (coastal forests) barriers. These forms of defense were neglected however, as their intent was to provide community wide defense, and not area specific defense which is being explored in this paper. Table 2 provides a summary of our findings.

Table 1 Percent Destroyed (cumulative) by Flow Depth and Community

	% Destroyed										
Depth (m)	**Ishinomaki**	**Kamaishi**	**Minamisanriku**	**Miyako**	**Ofunato**	**Onagawa**	**Otsuchi**	**Rikuzentakata**	**Sendai**	**Yamada**	**Kesennuma**
1	1%	12%	27%	6%	14%	8%	32%	17%	0%	19%	24%
2	16%	23%	30%	18%	25%	16%	11%	27%	3%	55%	36%
3	91%	46%	49%	53%	34%	35%	23%	43%	14%	75%	76%
4	96%	68%	70%	75%	57%	50%	56%	70%	57%	85%	89%
5	96%	77%	87%	91%	68%	66%	88%	83%	80%	91%	90%
6	95%	82%	89%	92%	65%	79%	97%	85%	97%	92%	93%
7	98%	88%	95%	91%	77%	88%	99%	91%	100%	94%	96%
8	98%	93%	99%	97%	86%	90%	99%	92%	99%	94%	97%
9	97%	93%	98%	100%	86%	88%	99%	98%	100%	91%	98%
10	99%	92%	98%	95%	87%	95%	98%	97%	100%	97%	97%
11	99%	95%	98%	94%	86%	99%	100%	99%	100%	97%	97%
12	99%	98%	99%	97%	85%	97%	100%	98%	100%	100%	99%
13	100%	99%	99%	94%	88%	97%	100%	99%	100%	97%	99%
14	94%	100%	99%	97%	95%	98%	100%	99%	100%	88%	99%
15	96%	94%	100%	78%	70%	99%	100%	99%	100%	100%	99%
16	93%	100%	99%	100%	91%	98%	100%	98%	100%	67%	96%
17	95%	100%	99%	100%	100%	97%	100%	100%	100%	100%	100%
18	100%	100%	98%	50%	100%	96%	100%	100%	100%	100%	100%
19	100%	97%	100%	0%	100%	96%	100%	100%	100%	100%	100%
20	100%	100%	100%	100%	100%	95%	100%	100%	0%	100%	100%

Table 2 City Tsunami Protection Checklist

City	**Tsunami Wall**	**Breakwater**	**Coastal Forest**	**Industrial/Commercial Front**
Kesennuma	N	Y	N	N
Ishinomaki	N	Y	N	Y
Kamaishi	N	Y	N	Y
Minamisanriku	Y	Y	N	N
Miyako	Y	Y	N	Y
Ofunato	N	Y	N	N
Onagawa	N	Y	N	N
Otsuchi	Y	Y	N	N
Rikuzentakata	Y	Y	Y	N
Sendai	N	N	Y	N
Yamada	Y	N	N	N

Unprotected Communities

To understand the effects of the urban environment, the team first identified those areas without commercial/industrial fronts that would serve as protection. These communities included: Kesennuma, Minamisanriku, Ofunato, Onagawa, Otsuchi, Rikuzentakata, Sendai and Yamada. Residential communities were either exposed directly to the initial and subsequent impacts of the tsunami waves or the urban configuration was such that it provided no relief from the hydrodynamic forces. The communities shown in Fig. 4 are Minamisanriku and Otsuchi. It can be observed that there is not an abundance of fishing warehouses or commercial/industrial mid-rise structures along the waterfront, leaving the residential properties fairly exposed.

Fig. 4 Minamisanriku (left) and Otsuchi (right) waterfronts

Community damage ratios were identified in Table 1 which shows the percent of buildings destroyed (regardless of structural type and occupancy) at each flow depth mark (in 1 meter increments). To understand how unprotected residential communities performed, areas were identified as being unprotected if they met the following criteria:

- Predominately residential
- No commercial/industrial areas blocking the wave path

Several cities (e.g., Rikuzentakata and Minamisanriku) meeting the criteria above were completely wiped out by the tsunami; these communities were not considered in the analysis above.

Ten subareas within seven cities were included in a more detailed analysis of the earthquake. The footprints of destroyed residential structures were extracted from the GIS data and tabulated to determine the damage ratio associated with each subarea area. The results are contained in Table 3 below.

Table 3 % Destroyed in Unprotected Residential Communities

City	% Destroyed	Max Height (m)
Ishinomaki	72.72%	6.5
Ishinomaki	82.70%	7.0
Miyako	74.83%	7.9
Ofunato	71.33%	10.3
Ofunato	68.92%	10.7
Otsuchi	99.42%	15.6
Otsuchi	93.79%	10.8
Sendai	94.70%	6.9
Sendai	96.37%	8.0
Kesennuma	88.29%	11.5

Protected Communities

Three cities (Ishinomaki, Kamaishi and Miyako) had residential regions that were considered "protected" by the urban environment. As stated before, these areas had large buildings along the water's edge that consisted of either reinforced-concrete commercial/residential structures, steel warehouses to accommodate the industrial/fishing communities or a combination of both.

Ishinomaki (Miyagi Prefecture)

Ishinomaki had a population of approximately 160,000 and was largely known as a shipping port with a large fish market. According to published records, approximately 46% of the city was inundated by the tsunami. The areas of focus for the study were directly east and west of the Kitakami River. To the west of the river lies large industrial factories. The east side is composed mainly of commercial/industrial areas. Both areas are populated by large steel industrial warehouses with the occasional reinforced-concrete commercial building. Single family residences are essentially non-existent in these areas. The residential areas directly north of the two industrial ports were considered "protected" for the analysis, as the water was forced through these areas before making contact with any of numerous wood-framed, single-family communities behind. A pocket of exposed, coastal residential structures can be found between these two areas, not protected by the larger commercial/industrial buildings, and exposed directly to the water. These areas were considered "unprotected" and can be found in Fig. 5.

Fig. 5 Ishinomaki "Protected" and "Unprotected" Residential Areas

The residential structures in the "protected" areas behind the commercial/industrial waterfronts recorded damage rates of 18% and 26% at 5.4m and 5.6m maximum depths, respectively. Approximately 83% of the residential structures in the "unprotected" residential coastal region however were destroyed. Using Table 1 as a general benchmark, it is expected that close to 95% of structures should be destroyed around the 5-6m mark (for the "protected" areas) and 98% should be destroyed at the 7m mark ("unprotected" area). Neglecting varying flow velocities and debris levels, a strong correlation between reduced damage within the community and a commercial/industrial front is inferred.

Kamaishi (Iwate Prefecture)

Kamaishi had a population of approximately 41,000 and is largely known for their steel production. Prior to the 2011 events, it was also known as a fishing port. Kamaishi was of particular interest because of the large, steel-framed, industrial warehouse with corrugated metal siding. Directly beyond the structure, a mix of single-family residences and low-rise mixed use populated the area, which can be seen in Fig. 6.

Fig. 6 Kamaishi “Protected” Areas

The structures behind the industrial warehouse (blue roof in Fig. 6) had a damage ratio of approximately 13% with an observed maximum height of 7.3 m. The city as a whole, experienced total damage of up to 88% of their structures at that same height, which can be found in Table 1.

Miyako (Iwate Prefecture)
Miyako had a population of approximately 60,000 people when the tsunami occurred and was known predominately as a fishing village. The shore along the Miyako fishing coast was lined with steel warehouses protecting both single-family residences and mixed-use structures. An area north of these protected areas which had no commercial/industrial front was also analyzed to compare results.

Fig. 7 Miyako “Protected” and “Unprotected” Areas

The analysis shows that those structures in the “protected” areas recorded a damage ratio of 32% with a maximum water depth of 7.9 meters. Areas in the “unprotected” areas were subject to the same water depth (7.9 m), however had a damage ratio of 75%.

DAMAGE SUMMARY

Overall, the percent of destroyed buildings in the unprotected zones ranged from 72% to 99%, with an average of 84%. The percent of destroyed buildings in protected zones ranged from 13% to 32%, with an average of 23%. Fig. 8 plots damage ratios for both unprotected and protected areas within the scope of the study. From the figure, it should be noted that no protected residential region suffered total losses that exceeded 40% of the building inventory. Those that were unprotected, however, experienced losses greater than 70%. Table 4 summarizes the findings of those cities with both protected and unprotected regions.

Table 4 % Destroyed for Protected and Unprotected Regions

	Residential Unprotected		Residential Protected	
City	% Destroyed	Max Height (m)	% Destroyed	Max Height (m)
Ishinomaki	72.72%	6.5	18.20%	5.4
Ishinomaki	82.70%	7	25.55%	5.6
Ishinomaki	82.70%	7	-	-
Kamaishi	43.01%	9.2	13.01%	7.3
Miyako	74.83%	7.9	32.24%	7.9

Large structures (industrial and commercial) performed much better than residential construction across most flow depths. This was expected as these structures were designed to withstand larger lateral forces based on seismic design. This was especially true for very high (maximum) flow depths, i.e., greater than 10m. Based on the data collected and analyzed from 15 zones in 11 cities, the percent of destroyed industrial/commercial buildings roughly doubles every 5 meters between maximum flow depths of 5m and 20m. For residential structures (unprotected), 7 meters appears to be a reasonable threshold for catastrophic damage, i.e., 75% or more of the buildings are completely destroyed.

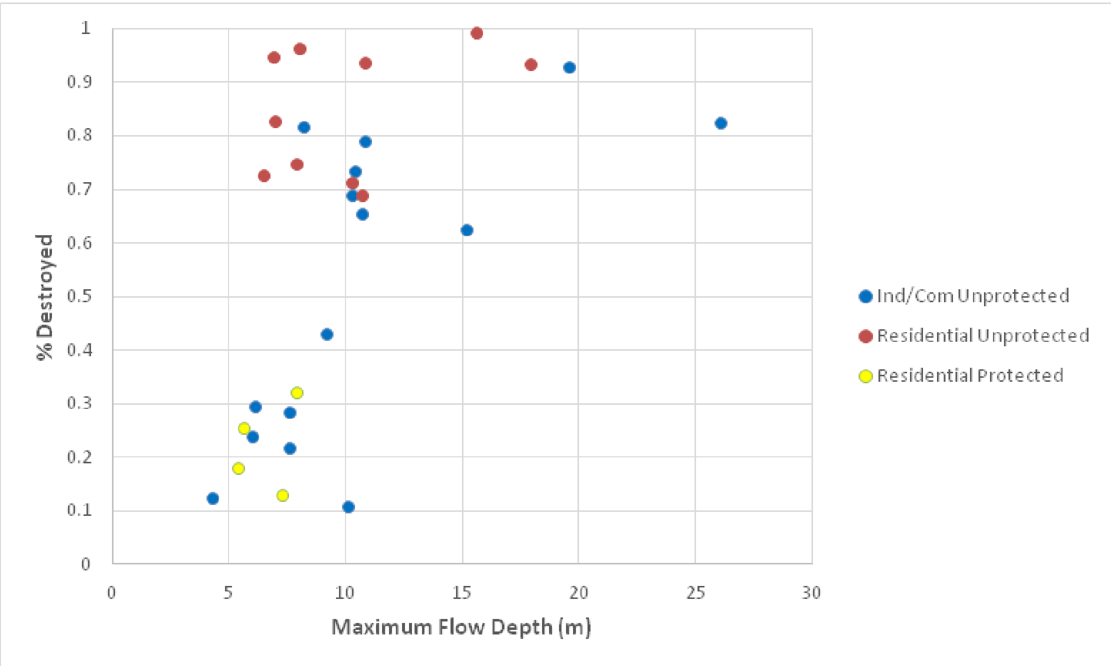


Fig. 8 % Destroyed vs. Occupancy and Protection Class

CONCLUSIONS

Statistics from the study areas show that the urban topography may have a significant impact on mitigating the damage to residential communities behind it. Residential areas that were protected from strong tsunami wavefronts by large industrial and/or commercial buildings were four times less likely to be destroyed by the tsunami.

We believe that the outcomes from this study will be useful in supporting the investigation of landuse and building construction practices that will mitigate the effects of moderate to large tsunami events. In California, where a moderate tsunami hazard is present, understanding the role of community configurations in either mitigating or exacerbating tsunami effects will help in preparedness planning as well as post-event response activities.

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