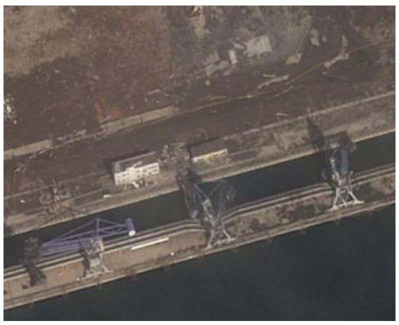
HAZUS Tsunami Benchmarking, Validation and Calibration



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The HAZUS Project Team would also like to thank the HAZUS Tsunami Steering Committee (Chaired by Ed Bernard) for their helpful discussions during the project on important priorities for this *Benchmarking, Validation and Calibration* task, and for their review and comments on this report. It is the hope of the Project Team that the preliminary results provided in this report will encourage further studies to develop a set of robust and comprehensive fragility functions for tsunami, especially for lifeline facilities for which little work has been done to date.

With the exception of the aerial and satellite imagery, all data used in this study for Sendai and Kesennuma were kindly made available by the **City Bureau of the Ministry of Land, Infrastructure, Transport and Tourism** (MLIT), published in March 2012.   The project team gratefully acknowledges this support and hopes that the findings of the current study will help to more fully understand the extent of devastation caused by the 2011 Tohoku earthquake and tsunami.

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1. INTRODUCTION

This report documents the results of a limited effort to benchmark modeling results generated from the newly-developed HAZUS Tsunami methodology. This report supplements a main report that contains detailed documentation on model development on building and lifeline damage functions, casualty estimation, debris estimation, and assessment of other socioeconomic losses. The main report is published under the title of *Tsunami Methodology Development.* Although quantitative comparisons between HAZUS-modeled output and observations of damage from actual events are made, this analysis is considered very preliminary in that data from only two events were used in the benchmarking process. In order to fully calibrate or validate the results, a more extensive analysis using more events and events representing a variety of conditions, e.g., buildings with different structural designs and construction, a variation in coastal topographies, earthquakes of different magnitudes, etc., is recommended. Useful insights, however, are still possible, especially regarding whether the results appear to be in the right ballpark. At the end of this report, we also provide recommendations on improvements that should be considered in order to ensure effective application of the methodology in the U.S.

1.1 Analysis Objectives and Scope

This analysis had two main objectives. The first objective was to validate regional damage results using the HAZUS Tsunami loss estimation framework using historical data from relevant earthquakes. In order to accomplish this, data from two earthquakes – the 2011 Tohoku, Japan earthquake and the 1964 Alaska earthquake – were used. The primary reasons for selecting these events were 1) the Tohoku event represents a significant earthquake with catastrophic damage in a country with seismic standards similar to the U.S., and 2) the 1964 Alaska earthquake, as it affected Crescent City, California, is considered a benchmark for evaluating tsunami damage potential for the U.S. The combination of these events helps us to understand the limitations of the current methodology and where data are needed to produce more robust results.

The second objective focuses on calibration of damage and fragility models for buildings and lifelines. While some calibration has been completed for building damage functions, very little has been done to calibrate the lifeline models. While the literature contains numerous references to studies where building fragility functions have been developed for earthquake shaking and tsunami effects (e.g., Koshimura et al., 2009a; Koshimura et al., 2009b; Gokon and Koshimura, 2011; Koshimura, 2012; Suppasri, 2013), very little information exists for lifeline fragility model development. And because of this, the approach used in this study to generate fragility functions for lifelines was to base this development on expert opinions, i.e., poll experts in each lifeline area for their “best guess” of probable damage levels for different flow depth ranges. This approach was used many years ago to develop an initial set of damage functions for buildings (see ATC-13, 1985). Therefore, there is a significant opportunity to calibrate lifeline fragility functions for tsunami effects, if ample data are available to help with this calibration or scaling.

In order to perform much of the analysis in this study, it was critical that partnerships within the development team and between the team and other outside investigators were used. Much of the coordination between the development team and colleagues in Japan was facilitated by Professor Shunichi Koshimura, Tohoku University. Although Professor Koshimura was not a project team member at the beginning of the study, it became very apparent that for the team to complete an analysis of the 2011 Tohoku event, it would be critical that a Japanese investigator join this effort. Professor Koshimura joined the HAZUS Tsunami project team in November of 2012.

Another aspect of this study focused on the use of remote sensing technologies to perform building and lifeline inventory tasks, as well as provide post-earthquake damage assessment for large regions within Sendai and Kesennuma. Although the primary data source for damage information in Japan was ground surveys performed by the Japanese Department of Municipal Affairs – Ministry of Land, Infrastructure and Transport (MLIT), the remote sensing analysis allowed the project team to review the damage assignments from a geospatial perspective. In addition, using Google Earth, the team was also able to view the reconstruction process of some key lifeline components, in order to validate the initial damage assignments. i.e., some damage assignments from the Japan government database indicated complete collapse of particular lifeline facilities. However, upon inspection of high-resolution images taken immediately after the earthquake and tsunami and shortly after, it was clear that many of these facilities were still standing and were not "washed away." See Section 2.2.4.1 for a more complete discussion of this analysis.

And finally, as suggested above, much more can be done to produce better fragility functions for tsunami effects, especially for lifelines. Data from several foreign earthquakes, such as the 2011 Chile earthquake, or the 2004 Indian Ocean earthquake, and other areas in the U.S. affected by the 1964 Alaska earthquake (e.g., Hawaii, the coast of Oregon) could be used to further test the methodology and models developed in this study. Specific recommendations are provided in the last section of this report on further studies to improve the overall tsunami modeling methodology.

1.2 Methodology and Assumptions

The methodology used in this study to perform the benchmarking task is illustrated in Figure 1 below. Various analysis and data import/export modules are identified. Modules identified in green are associated with steps that involve importing data from the Tohoku earthquake event. Data are in the form of building or lifeline inventory databases (counts of buildings, building construction types, building footprint sizes, number of stories, lifeline component types), hazard information (tsunami flow depths), damage information (number of damaged buildings and lifelines, damage levels), and casualty data (mainly number of deaths). The white block modules are the HAZUS Tsunami calculation steps. Using the data on the Tohoku earthquake, HAZUS Tsunami calculates the number of damaged buildings and lifelines by simulating a repeat of the 2011 Tohoku earthquake. The output is then compared with the actual damage totals and distributions generated from the field surveys conducted after the earthquake.

A similar benchmarking process is followed for the analysis of the effects of the 1964 Alaska earthquake on Crescent City, California, albeit less rigorous and extensive. Unfortunately, not much quantitative information was available to the development team on this event or for Crescent City. Perhaps, adding an expert on the Crescent City experience would be useful in future studies.

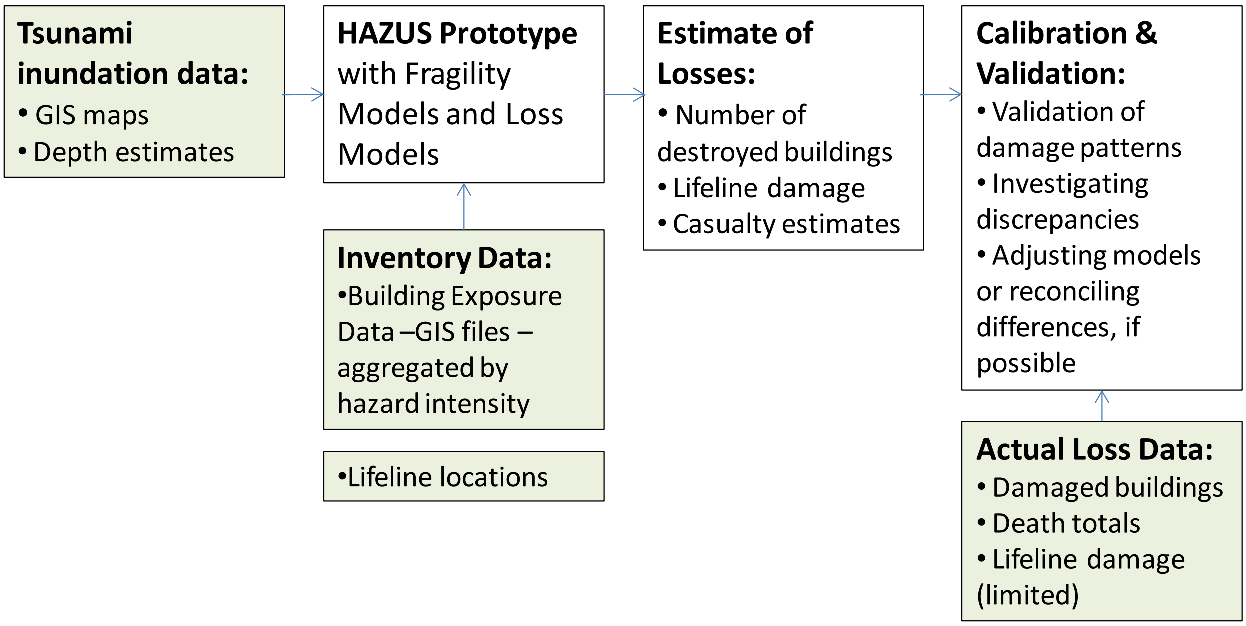


Figure 1: Benchmarking Flowchart for Tohoku, Japan Earthquake

In performing this benchmarking analysis, a number of assumptions were made; many limiting the long-term efficacy of this study's conclusions. Much of what was done in this study to benchmark early HAZUS model results was based on comparisons with limited (and sometimes old data, as was the case with the 1964 Alaska earthquake study) datasets. In the case of the 2011 Tohoku, Japan earthquake and tsunami, only two areas that were affected by this devastating event were used; data for many more areas are available. And it is clear that for some comparisons – especially those related to lifeline system or component performance – larger datasets that include a variety of urban development settings would be more desirable. However, even with these limitations, the results from the present conclusions do allow enough insight into whether the models and methodologies that have been built into HAZUS to address tsunami hazards and effects are reasonable.

Some of the major assumptions made in this study include:

1. The MLIT data used in the analysis of building and lifeline performance in the Tohoku earthquake and tsunami was used as received. That is, no attempt was made to check or validate these datasets. An interpretation of damage states and their meanings, however, was `made in order to fit the damage data into "HAZUS" damage categories. These associations are discussed in Section 2.2.1 (Building Damage States) and in Section 2.2.4.1 (Lifeline Damage States).

2. For some datasets, the description of damage (when translated from Japanese to English) may have lost its initial or implied meaning. Even though the project team contacted its Japanese

partners, the meaning in Japanese may not have been clear. With our Japanese partners, we did the best to preserve what we interpreted the original descriptions to mean. Further discussions with the developers of the datasets (field teams who contributed to the MLIT database) would be needed to ensure the proper interpretation of these descriptions.

3. For buildings, because of the large datasets available for the two study areas and because data in all damage categories (including no damage) were included, we have assumed that we are working with complete building inventory databases, i.e., data on all buildings affected by tsunami inundation are included in the MLIT datasets.
4. For lifelines, we are assuming that only facilities that were reported as having damage are included in the MLIT dataset. We know this is the situation with bridges and roads; we assume this is also the case for all utility lifeline components.
5. The tsunami flow depths used in our analysis are taken directly from the MLIT database. Furthermore, the flow depths represent the maximum within a particular grid cell size (100m by 100m). We have used these grid-based estimates to represent the flow depths at each building site, as well as for every lifeline facility. Therefore, errors in flow depth assignments are possible; some examples of these errors are described in Section 2.2.4 (Lifelines).
6. The analyses that were conducted for Sendai and Kesennuma were done for only a portion of the total area of each municipality. And for Sendai, only a portion of the inundated area was evaluated, i.e., essentially the areas closest to the ports. Therefore, the damage reported in this study may be less than that reported from other sources for the entire municipality.
7. While ground photos and high-resolution oblique imagery were used to help characterize construction types for buildings, only general structural categories were adopted in describing Japanese construction, i.e., concrete, steel and wood. In some cases, this led to unexpected damage trends, e.g., steel buildings with higher damage rates than wood buildings for the same flow depths. A possible explanation for this unexpected trend is provided in Section 2.2.2. (Building Damage Results).

1.3 Events Considered

As discussed above, two events were used in this benchmarking analysis: the 2011 Tohoku, Japan earthquake and the 1964 Alaska earthquake. Table 1 below shows the various datasets that were available for this analysis. In addition, we note the major challenges that the development team faced as it assembled these datasets. The most complete datasets came from Japan for the two study regions. In addition to these two cities, extensive datasets are available for another dozen or more cities affected by the Tohoku earthquake. Only very limited data was available to the development team for Crescent City. Much research is being done to understand the effects of tsunamis along the coasts of California and Oregon, however, these data are not currently available either because it is in the process of being generated or the data have not been critically reviewed by the general research community.

In the future, rich datasets for other cities in Japan affected by the Tohoku event could be considered. These areas include: Ishinomaki, Onagawa, Minami-sanriku, Rikuzen-takata, and Kamaishi. Other possible events/areas include: Dichato and Constitucion, Chile (2011 Chile earthquake) and the 2004 Indian Ocean earthquake and tsunami.

Table 1: Events Studied in this Analysis

Earthquake	Case Study Area	Datasets	Challenges
2011 Tohoku Earthquake	Sendai area	▪Flow depths ▪GIS demographic data ▪GIS building inventory data ▪Actual building damage data ▪Limited damage information on lifelines ▪Deaths by municipality and block level	▪Limited lifeline data, both pre- and post-earthquake ▪No flow rate or debris impact observations readily available
2011 Tohoku Earthquake	Kesennuma	▪(same as Sendai)	▪(same as above)
1964 Alaska Earthquake	Crescent City	▪HAZUS inventory (pre-1970) ▪Archived damage data	▪Only destroyed buildings recorded ▪No lifeline damage data ▪No flow rate or debris impact observations available

2. 2011 Tohoku Earthquake and Tsunami

The magnitude 9.0 Mw March 11, 2011 Tohoku earthquake and subsequent tsunami was one of the most powerful earthquakes recorded in modern history, resulting in one of the most costly natural disasters known to man. The USGS reported a maximum PGA of 2.7g recorded in Miyagi Prefecture – see http://nsmp.wr.usgs.gov/ekalkan/Tohoku/index.html. The National Police Agency of Japan has reported (as of 2/20/2013) 15,880 deaths and 2,694 still missing – see http://www.npa.go.jp/archive/keibi/biki/higaijokyo e.pdf., 397,918 properties have been reported as a "total collapse" or "half collapse." Estimates by the World Bank predict $235 billion (USD) in economic costs. For this study, two areas of interest were chosen: Sendai and Kesennuma. Both were severely damaged by the tsunami which reached elevations up to 10m and 15m+ for Sendai and Kesennuma, respectively. The two cities were chosen because of the large inventory and damage datasets available and the contrasting geographic features of both the land and the shoreline. Sendai's flat agricultural land and straight shoreline contrasts drastically with Kesennuma's mountainous features within the bay. Figure 2 shows perspectives of both areas

Sendai, the capital city of Miyagi prefecture, is the largest and most populous city (1,055,770 people, as of 2/2013) in the Tohoku region. The area of interest includes the coastal regions north of the Sendai Airport to the Sendai port (approximately 7.5 miles of coast). Most of Sendai's inhabitants reside around the administrative center of the Aoba-ku ward, however those most affected by the tsunami lived in the

Wakabayashi and Miyagino coastal wards, which are open, flat areas largely occupied by agricultural fields. A coastal forest once occupied the shore, however was eventually destroyed by the tsunami.

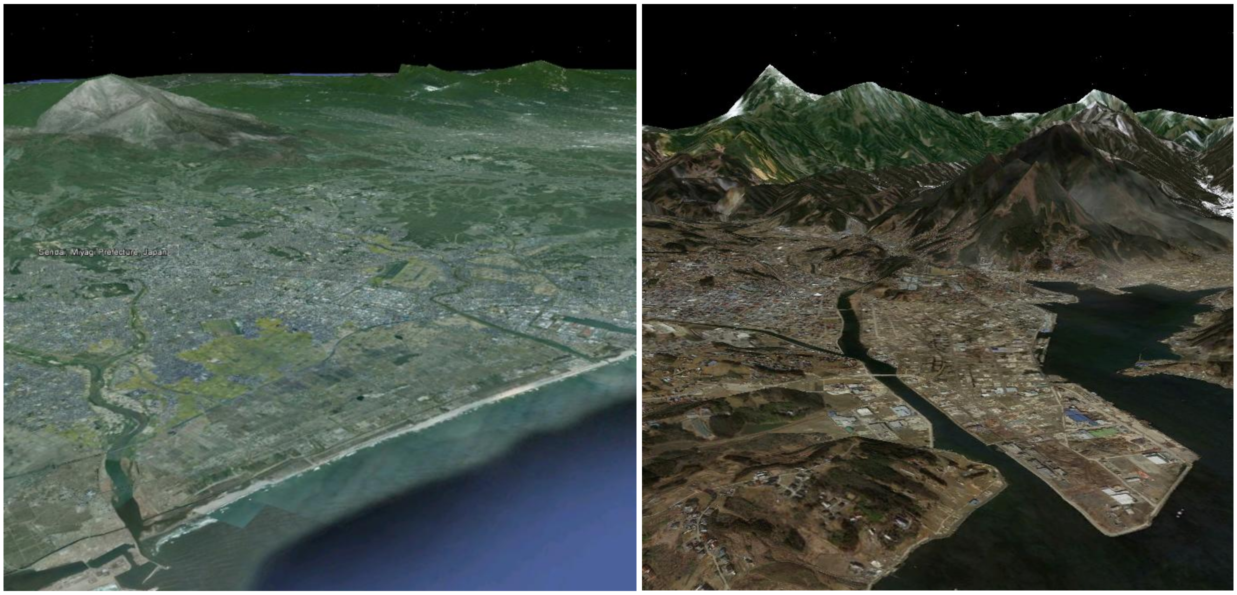


Figure 2: (Left) Sendai's flat coastline (Right) Kesennuma's mountainous bay

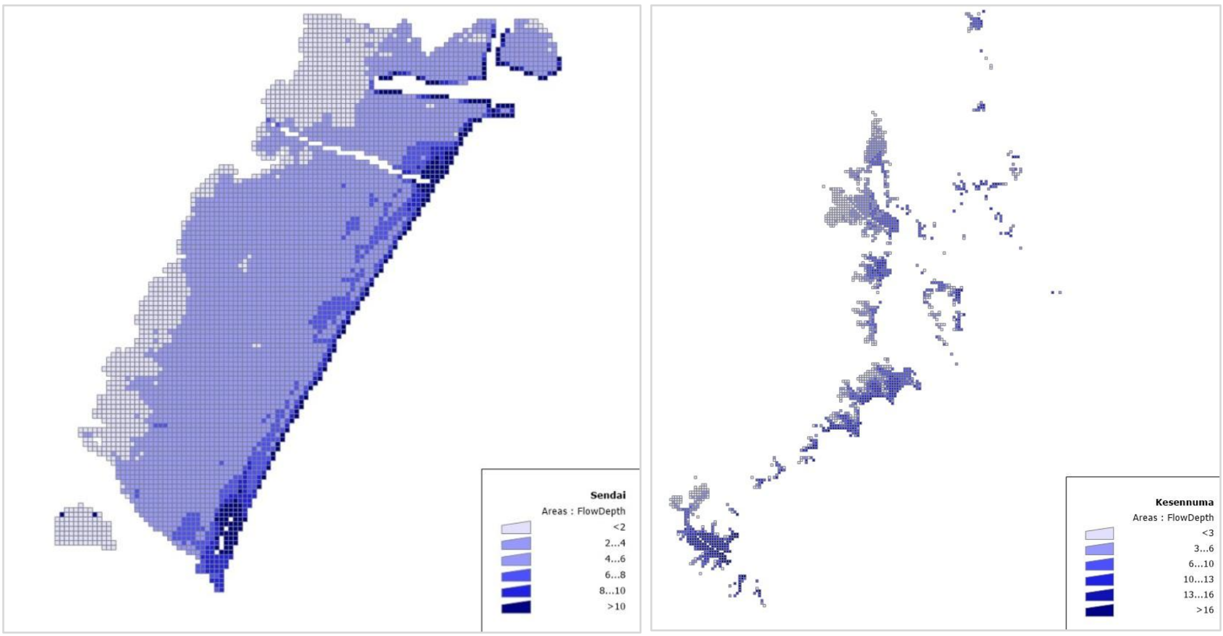
Kesennuma (population of 69,089, as of 5/2013) is a commercial fishing city in the northern most region of Miyagi prefecture. The city suffered a substantial amount of damage from both the tsunami and fire following. Most residential, commercial and industrial structures are located within a few kilometers of the water.

2.1 Data for the 2011 Tohoku Earthquake

Aggregated datasets for the two study areas were provided to the project team by several Japanese collaborators including Professor Shunichi Koshimura of Tohoku University (HAZUS Tsunami Development team member) and Professor Fumio Yamazaki of Chiba University. 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/lifeline damage 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 and lifeline data were provided in a GIS format (.shp) with instructions/explanations 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.

2.1.1 Maximum Tsunami Flow Depth

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 layer and the corresponding flow depth was then assigned to the structure. Figure 3 below shows grid maps for both Sendai and Kesennuma with maximum flow depths on a grid cell basis. Flow depths for Sendai reach 10 meters; for Kesennuma, flow depths reach as high as 16 meters.

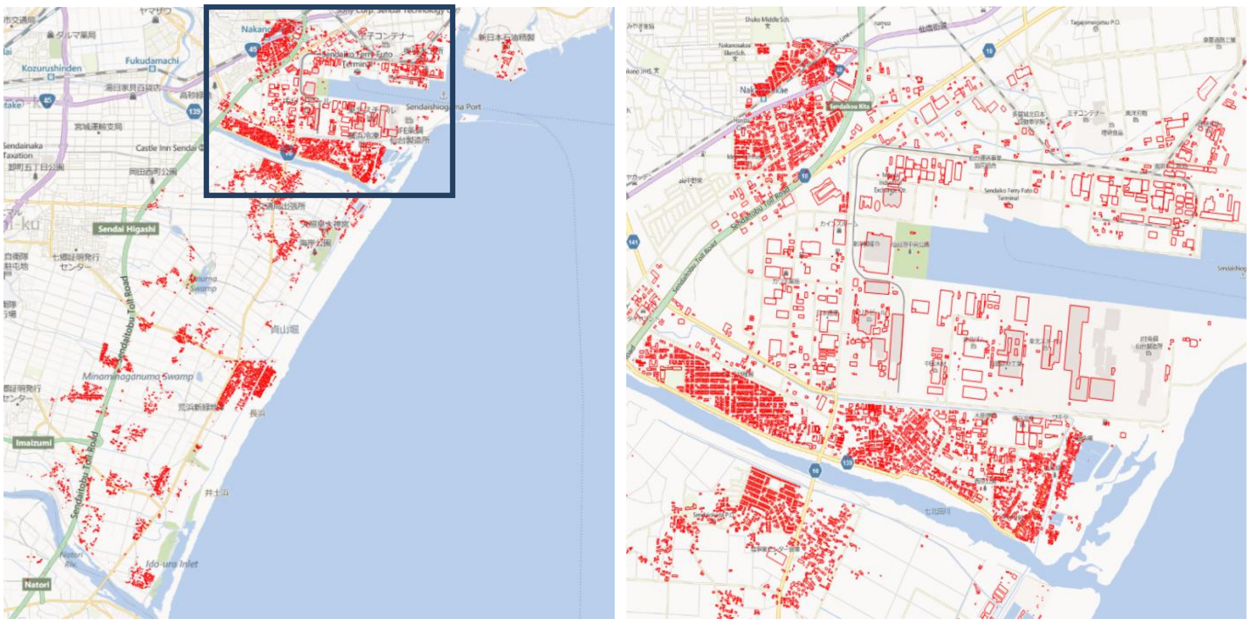


Sendai **Kesennuma**

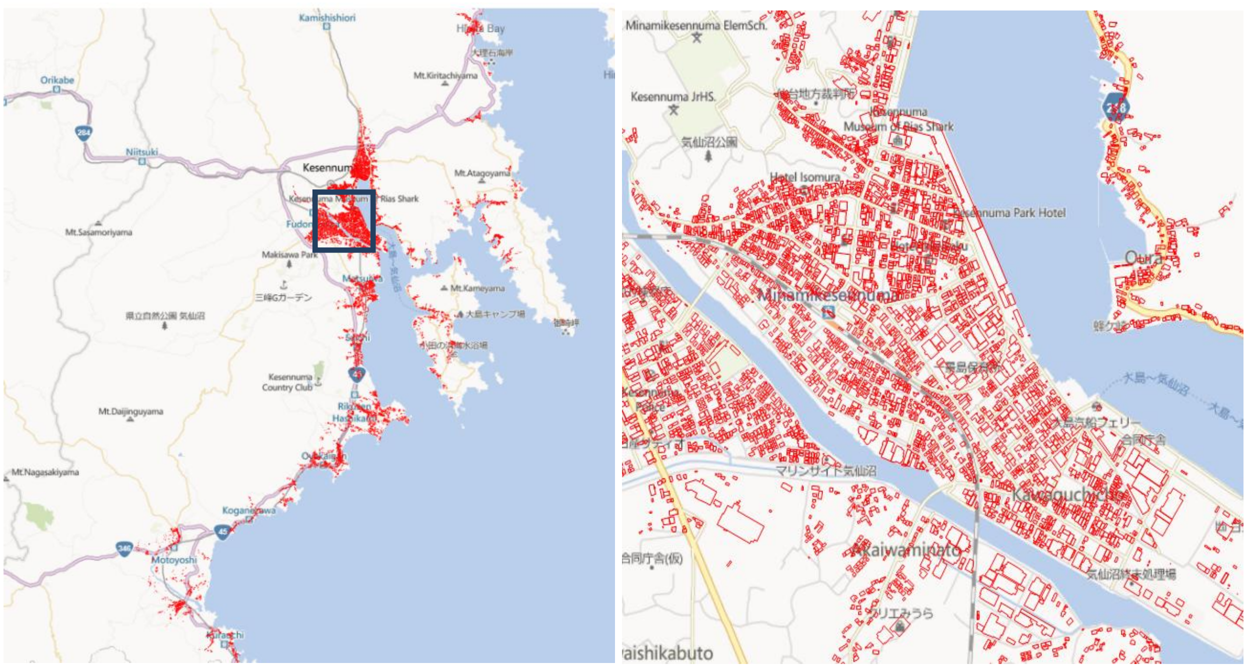
Figure 3: Maps showing Maximum Flow Depths in meters in Sendai and Kesennuma

2.1.2 Building Database

The Sendai and Kesennuma inventory databases contain 11,683 and 19,815 building records, respectively. Each record is assigned a unique ID that links the polygon (building footprint) to the detailed building summary. The 11,683 structures in the Sendai region are contained within 4 km of the coast and extend north of the Sendai airport to the Sendai industrial ports, just south of Tagajo. The mountainous geography of Kesennuma results in patches of densely populated regions along the bay. This database includes a vast majority of the structures along the coast and within the inundation zone. Figure 4 shows the building footprints for each of our study areas.



(Left) Map showing building footprint extent for Sendai (Right) Zoomed in view of Sendai Port



(Left) Map showing building footprint extent for Kesennuma (Right) Zoomed in view of port and downtown area

Figure 4: Building Footprints for Sendai and Kesennuma.

The following information (if recorded during the field survey) is available for each building footprint: occupancy, structural type, number of residents occupying each structure (if residential and for Sendai only), 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.

2.1.2.1 Building Occupancy and Structural Categories

The Japanese database includes 15 different occupancies, ranging from single-family dwellings to defense facilities. In order to format these data into categories that could be used within HAZUS Tsunami, the occupancies were re-mapped into more general categories. See Table 2 for this mapping scheme.

Table 2: Mapping of Japanese Occupancies to HAZUS Tsunami Occupancies

Japanese Occupancy	HAZUS Occupancy
Residential	Residential
Shared Dwelling	
Dual Purpose (Commercial)	
Dual Purpose (Industrial)	
Other Residential	
General Commercial	Commercial
Commercial (Office, Bank)	
Other Commercial	
Transportation/Storage	Industrial
Industrial	
Processing Plants	
Other Industrial	
Public Facilities	Public
Government Facilities	Government
Agricultural Facilities	Agricultural

Tables 3 and 4 provide detailed breakdowns of occupancy as a function of tsunami flow depth (m) for Sendai and Kesennuma, respectively. Specific occupancy types include: residential (R), commercial (C), industrial (I), mixed (M), public (P) and unknown. For Sendai, 11,683 buildings are contained in the study database. Most of the buildings are residential structures (about 70%) and approximately 40% of those buildings experienced flow depths of 4 meters or higher. In addition, the vast majority of buildings are constructed of wood (64%) while 27% were of unknown structural type. Steel buildings accounted for approximately 6% of the total; reinforced concrete structures made up about 3% of the total.

Table 3: **Breakdown of Occupancies and Structural Types for Sendai (Study Area only)**

Sendai	Occupancy Type	Flow Depths (m)						Subtotal
		0-2m	2-4m	4-6m	6-8m	8-10m	10+	
	Residential	2192	2578	2929	461	11	1	8172
	Commercial	291	255	102	7	1	1	657
	Industrial	424	754	581	56	10	0	1825
	Mixed	104	167	150	27	0	0	448
	Public	89	73	118	9	2	0	291
	Unknown	53	104	103	28	2	0	290
	Total	**3153**	**3931**	**3983**	**588**	**26**	**2**	**11683**
Sendai	**Structure Type**	**Flow Depths (m)**						**Subtotal**
		0-2m	**2-4m**	**4-6m**	**6-8m**	**8-10m**	**10+**	
	Wood	2309	2534	2266	391	14	0	7514
	Steel	280	278	116	20	1	2	697
	RC	111	119	95	13	1	0	339
	Unknown	453	1000	1506	164	10	0	3133
	Total	**3153**	**3931**	**3983**	**588**	**26**	**2**	**11683**

In Kesennuma, 19,815 buildings are contained in the study database. As with the Sendai dataset, the vast majority of the buildings are residential structures (62%) and approximately 60% of the buildings experienced flow depths of 3 meters or higher. The predominant structural type is wood frame.

Table 4: Breakdown of Occupancies and Structural Types for Kesennuma (Study Area only)

Kesennuma	Occupancy Type	Flow Depths (m)						Subtotal
		0-3m	3-6m	6-9m	9-12m	12-15m	15+	
	Residential	4939	3600	1979	1276	540	49	12383
	Commercial	1102	1285	380	160	57	0	2984
	Industrial	228	441	341	89	19	5	1123
	Mixed	76	77	40	20	13	2	228
	Public	234	180	69	69	14	5	571
	Unknown	1316	589	329	206	72	14	2526
	Total	**7895**	**6172**	**3138**	**1820**	**715**	**75**	**19815**
Kesennuma	**Structural Type**	**Flow Depths (m)**						**Subtotal**
		0-3m	**3-6m**	**6-9m**	**9-12m**	**12-15m**	**15+**	
	Wood	4672	4372	2050	1245	445	29	12813
	Steel	57	72	34	13	6	2	184
	RC	113	124	29	31	2	1	300
	Unknown	3053	1604	1025	531	262	43	6518
	Total	**7895**	**6172**	**3138**	**1820**	**715**	**75**	**19815**

Figure 5 provides a graphic representation of the overall distribution of structural types for both study areas. In both areas, the predominant structural type is wood frame. In Japan, a wood-frame structure would consist of a concrete foundation or mat on which sits a post-and-beam construction, unlike the stud wall on reinforced concrete floor slab typical in the U.S. The structures are generally one or two stories. The typical footprint for residential houses is approximately 110 square meters.

The steel construction in areas affected by the tsunami is generally a steel-frame building with light metal sheathing on the outside (light metal framing). These structures are ideal for warehouses or manufacturing facilities because of their long spans and open floor plans. They also tend to be low rise, that is, less than 3 stories.

The reinforced-concrete buildings in the affected areas are generally built with standards similar to the U.S. Both reinforced-concrete frame and shear-wall buildings are present. In addition, most reinforced-concrete structures are four stories or lower. Those taller than four stories are typically hotels, apartments, hospitals or schools.

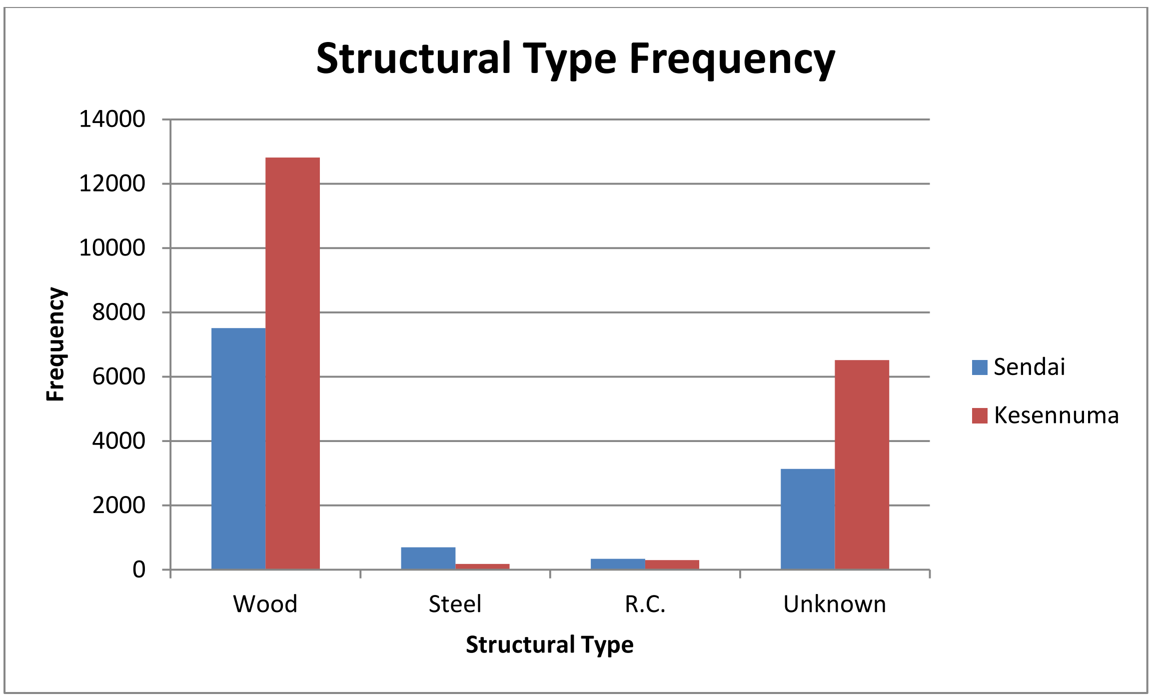


Figure 5: Distribution of Buildings by Structural Type for Study Areas

2.1.2.2 Number of Stories

The number of stories for each structure is given in the MLIT Database for both cities. Stories ranged from 1-10 in Sendai and 1-6 in Kesennuma. The vast majority of the structures in both areas are wood-framed, single-family homes, thus, the typical story height is one or two stories. Figure 6 shows the distribution of story heights by construction type for both Sendai and Kesennuma.

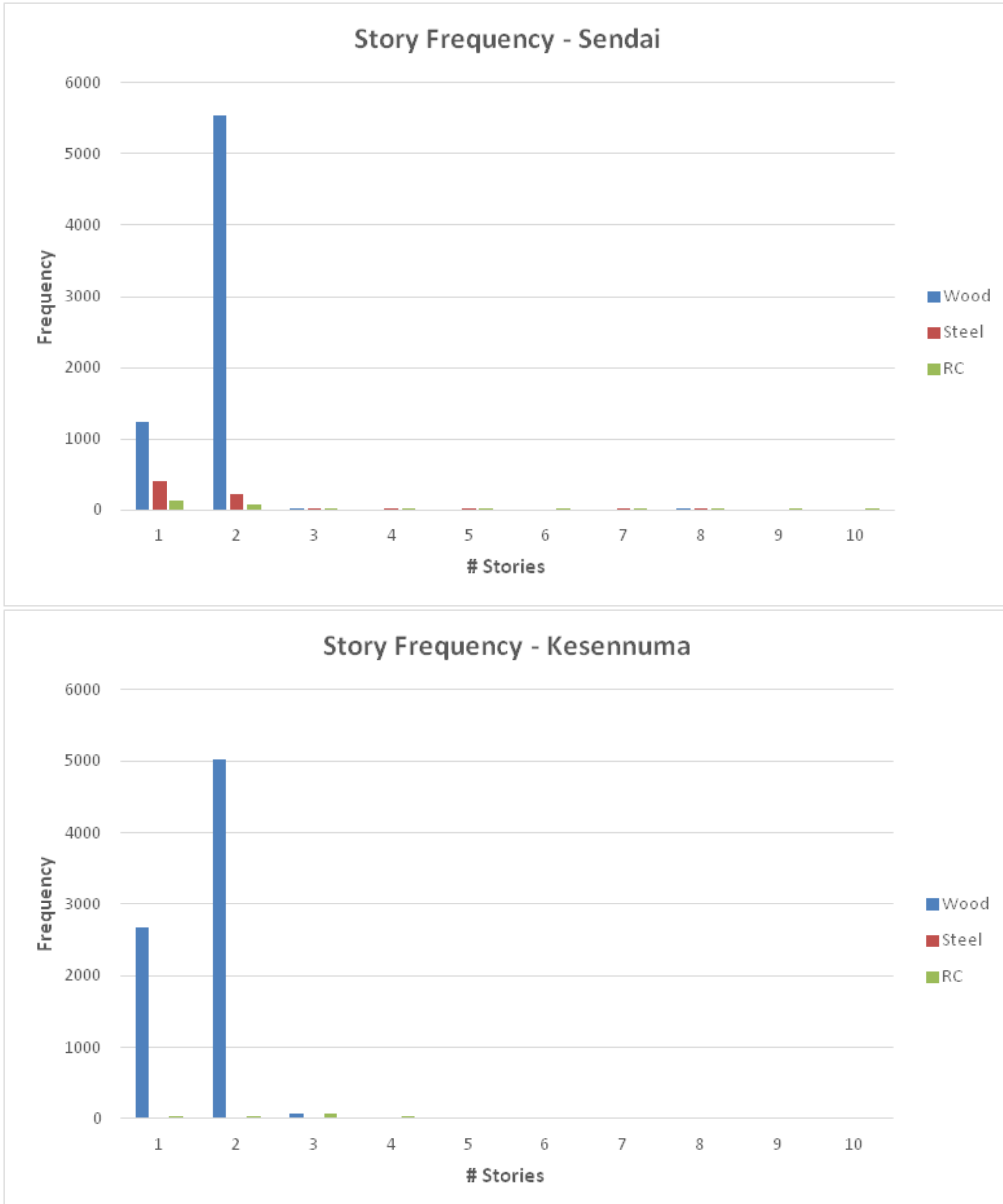
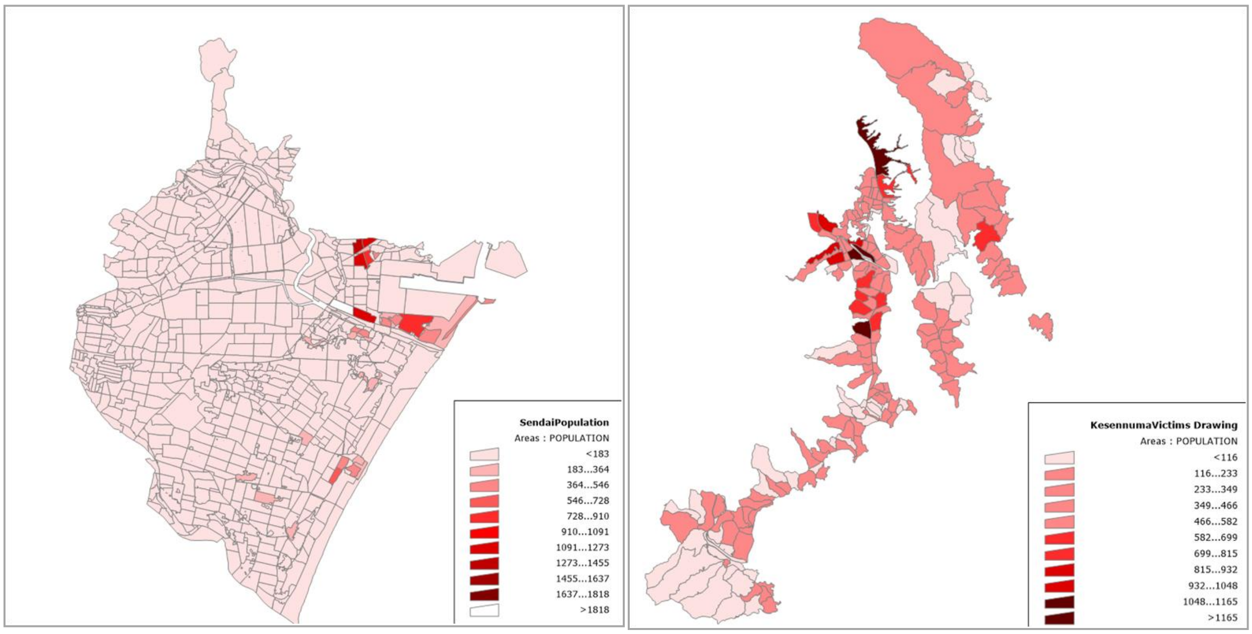


Figure 6: Distribution of Buildings by Number of Stories and Structural Type for Sendai and Kesennuma

2.1.3 Number of Residents

The Sendai database included the number of residents inhabiting each structure. Unfortunately, this information was not available for Kesennuma. However, population estimates by government or municipality units was available for both areas. Figure 7 shows a population map for both areas. In Sendai, the largest population (within the area of interest) resides along the coast near the opening of the Hirose River and near the port. In addition, much commercial and industrial construction exists around the port thus implying a large daytime population in that area. In total, roughly a million live in the Sendai region, however, it is estimated that less than 2% lived in areas that were affected by the tsunami.

The population of Kesennuma is about 70,000 people. The most populous areas in this region are on the western side of Kesennuma Bay. Low-lying areas of Kesennuma – where most of the population resides - are surrounded by mountainous areas to the north and west. These low-lying areas are subject to significant tsunami effects because of the low elevations and because they are located at the mouth of the Okawa river which empties into Kesennuma Bay.



Sendai **Kesennuma**

Figure 7: Population by Block for Sendai and Kesennuma in Tsunami-affected Areas

2.1.4 Lifelines and Transportation Facilities

In addition to building inventory data, lifeline and transportation system data were also available for both cities. Although not as extensive as the building inventory data, the lifeline database does provide locations and damage states for those lifelines or facilities that were affected by the tsunami. The following is a list of lifeline systems and components included in the MLIT database:

- Gas: Manufacturing Facility, Storage Facility and/or Power Distribution Facility
- Ports: Embankment, Revetment, Flood Gate, Weir, Gate Gutter, Aircraft Parking and/or Container Yards/Cranes
- Roads: Roads, Bridges and/or Tunnels
- Sewage: Treatment Plant, Pump Plant and/or Specialty
- Water Supply: Intake Facilities, Water Treatment Facilities, Water Distribution Facilities and/or Specialty

A more detailed discussion of lifeline system inventories is provided in Section 2.2.4 where we summarize their performance in the Tohoku earthquake.

2.2 Damage Analysis

This section describes the different damage datasets received from the Japanese government through our project team member (Koshimura) and partners. We first discuss the results for buildings, then lifeline facilities, and finally impacts on people, i.e., casualties.

2.2.1 Building Damage States

The Japanese data classified damage in one of seven categories: washed away (structure is no longer present due to buoyant or hydrodynamic forces), collapsed (structure is visible, however considered a complete loss), inundated above the first floor, major, moderate, slight and none. For our purposes, damage states had to be mapped into categories that are used by the HAZUS methodology. In HAZUS, the following damage states are used:

- Slight – Not used for tsunami
- Moderate – includes limited and localized damage to elements on the first floor (diagonal cracks in shear walls, limited yielding of steel braces, cracking and hinging of flexural elements)
- Extensive – includes local collapse of structural elements and nonstructural components, e.g., out-of-plane failure of walls due to tsunami flow
- Complete – structures that are still standing, but a total economic loss, or structures that have sustained partial or full collapse but remain largely in place, or structures that have been "washed away" by tsunami flow

Table 5 shows how the Japanese damage descriptions were mapped into the HAZUS damage categories.

Table 5: Mapping of Japanese Damage Descriptions to HAZUS Damage States

Japanese Damage Level/State		HAZUS Damage State
1	Washed Away	Complete
2	Collapsed	
3	1st Floor Inundation	Extensive
4	Major	
5	Moderate	Moderate
6	Slight	Slight/None
7	None	

2.2.2 Building Damage Results

The distribution of buildings by damage state and flow depth is shown in Tables 6 and 7 for Sendai and Kesennuma, respectively. In the case of Sendai, 11,683 were included in the Japanese database, with over 80% experiencing some level of damage (i.e., moderate, extensive or complete). As stated earlier, 40% of these buildings experienced flow depths of 4 meters or higher. For Kesennuma, 19,815 buildings were contained in the Japanese database, with over 90% experiencing some level of damage. In fact, for Kesennuma, over 75% of the buildings suffered complete damage. Figure 8 shows a before and after image of an area located just north of Kesennuma port. The post-earthquake image to the right shows not only devastation to building stock but at least one bridge (located in the lower right-hand corner) has been washed away by the tsunami.

Table 6: Number of Buildings by Damage State Category and Flow Depth - Sendai

Damage State	Flow Depth (meters)						
	0-2	2-4	4-6	6-8	8-10	>10	Total
None/Slight	1,727	267	9	1	0	0	2,004
Moderate	1,205	1,483	30	0	0	0	2,718
Extensive	185	978	814	6	2	0	1,985
Complete	36	1,203	3,130	581	24	2	4,976
Subtotal	3,153	3,931	3,983	588	26	2	11,683

Table 7: Number of Buildings by Damage State Category and Flow Depth - Kesennuma

Damage State	Flow Depth (meters)						
	0-3	3-6	6-9	9-12	12-15	>15	Total
None/Slight	1,554	27	16	0	0	0	1,597
Moderate	532	11	8	0	0	0	551
Extensive	1,812	520	125	45	5	2	2,509
Complete	3,997	5,614	2,989	1,775	710	73	15,158
Subtotal	7,895	6,172	3,138	1,820	715	75	19,815

Figure 8: Before (1977) and after Image (3/13/2011) of Northern Kesennuma
(Source: http://saigai.gsi.go.jp/20110311eqBeforeAfter/html/015f.html)

In order to understand how each HAZUS damage state varied as a function of flow depth, several different evaluations of the data were performed. First, the mean and median flow depths associated with each damage state and for each geographic area were calculated. These results are shown in Table 8. What the table shows is that the relationship between damage state and flow depth is much more abrupt in the case of Kesennuma. Sendai results show a more gradual increase of damage state with flow depth. Perhaps, one reason for this is that the topography in the Sendai area is more gradual thus eliminating any sudden changes in flow velocity and/or flow depth. The Kesennuma area is a much more complicated geography with mountainous areas surrounding low-lying regions (regions where the most populous areas are.) Furthermore, the area of Kesennuma most impacted by the tsunami happens to be near the source of the Okawa river where possible focusing effects from incoming waves is possible.

To study the variation of each damage state as a function of flow depth, Figure 9 is presented for both Sendai and Kesennuma. For Sendai, each curve (with the exception of slight/none) suggests that each damage state has a central value with a significant likelihood of being either higher or lower than that value, i.e., a wide range of flow depths can lead to a particular damage state. For the damage state category of slight/none, the data suggests that if the flow depth is lower than 2 meters, the chance for significant damage is low.

A plot of damage state frequencies by flow depth for Kesennuma shows a very different trend than above. Rather than showing nice central values for each damage state (as demonstrated with the Sendai data), the curves in Figure 9 for Kesennuma are highest at lower flow depths and rapidly decrease with increasing depths. There could be several explanations for this. One possible explanation is that very few buildings were in areas of high flow depth. This is generally true for all damage states except "complete." Another explanation is that the damage is driven by another factor besides flow depth. In Kesennuma, because of the topography and geographic configuration of the area, it is likely that the flow velocities in Kesennuma (outflow velocity in Kesennuma Bay estimated at 11m/s by Fritz et al., 2011) were much higher than in Sendai (flow velocity estimated at about 6 m/s for Sendai plain, Robertson/Google/ASCE, 2011). Thus, a higher percentage of buildings in Kesennuma would suffer extensive and complete damage at equivalent flow depths. However, a thorough investigation of the causes and types of damage observed in each of these areas should be performed in order to validate these assumptions.

Table 8: Mean and Median Values of Flow Depth for each Damage State

	Sendai Flow Depth (m)		Kesennuma Flow Depth (m)	
Damage State	Median	Mean	Median	Mean
Slight/None	1.30	1.27	0.00	0.35
Moderate	2.30	2.10	0.60	0.79
Extensive	3.90	3.63	1.70	2.40
Complete	4.50	4.65	5.30	5.38

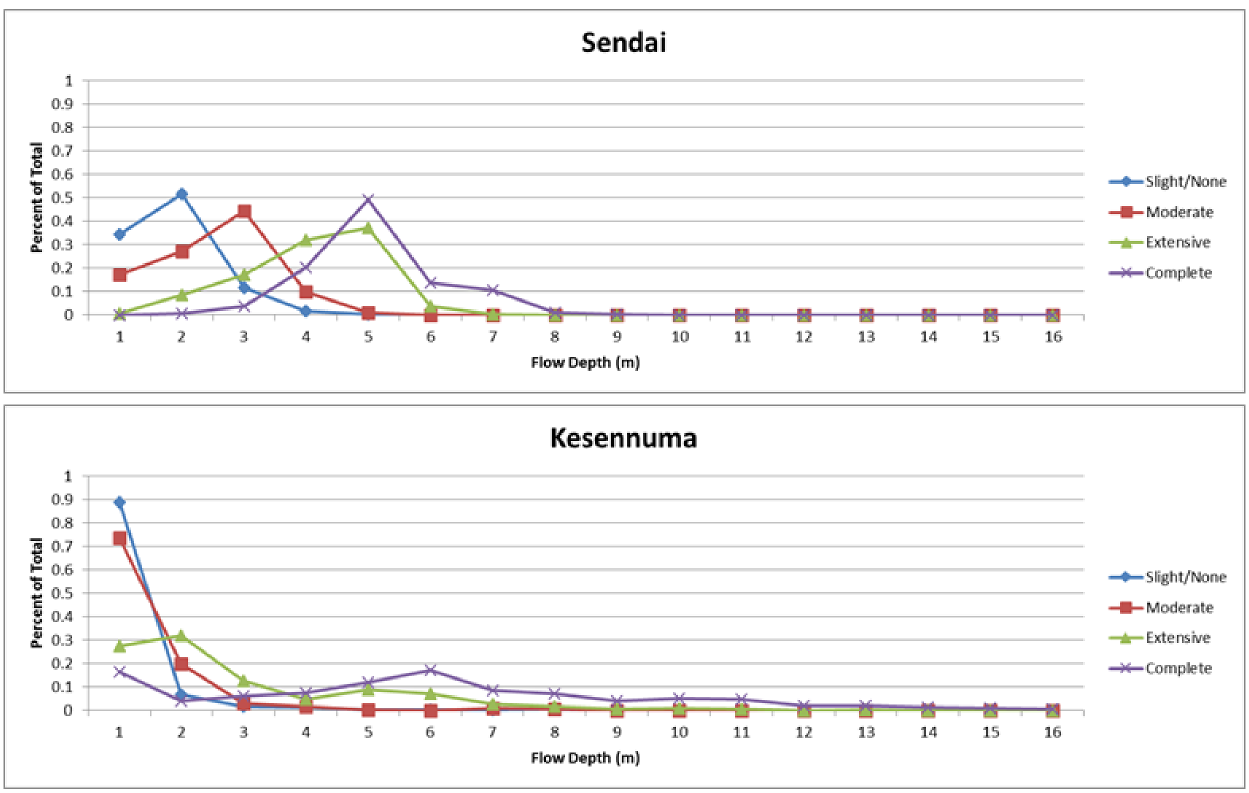


Figure 9: Distribution of Damage States by Flow Depth for Sendai and Kesennuma

The damage data for each city was also reviewed for differences in damage potential due to different structural types. The Japanese data provided very basic descriptions of structural type – see Section 2.1.2.1 more details. Most of the buildings in the two areas are built of wood construction. In addition, there are some steel and reinforced-concrete buildings. Figures 10 and 11 show a comparison of damage trends for the two areas. Note that damage in these figures is defined as including moderate, extensive and complete. In both cases, the cumulative curve is plotted only to 10 meters.

For Sendai, the curves show an interesting trend. The cumulative curves for both steel and reinforced-concrete are higher than the curve for wood frame. One would expect the reverse, i.e., wood-frame would be higher than the other two. At this point, no obvious explanation is clear. As stated earlier, the precise definition of a steel building is not clear. In several visits to the impacted area after earthquake, significant damage to many low-rise, steel-frame buildings was observed. These buildings tend to be warehouses or manufacturing facilities with metal sheathing outsides. The types of damage that were observed were destroyed sides or walls, especially at the lower story levels. As for reinforced-concrete buildings, no specific explanations are evident, other than statistical variability. A major recommendation from this study is to redo the analysis with additional damage data from other coastal cities in Japan. This information is available for many other cities but analysis of this data is beyond the present scope-of-work.

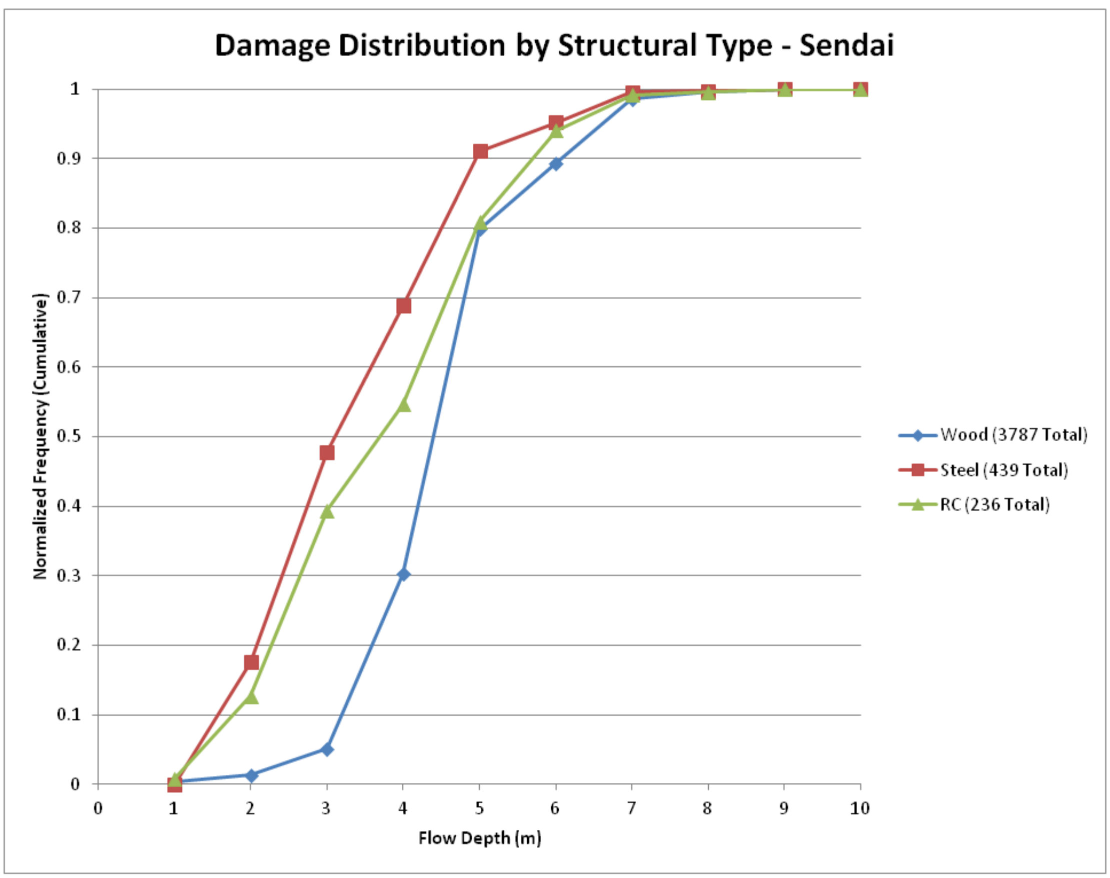


Figure 10: Damage Distributions by Structural Type for Sendai (Study Area only)

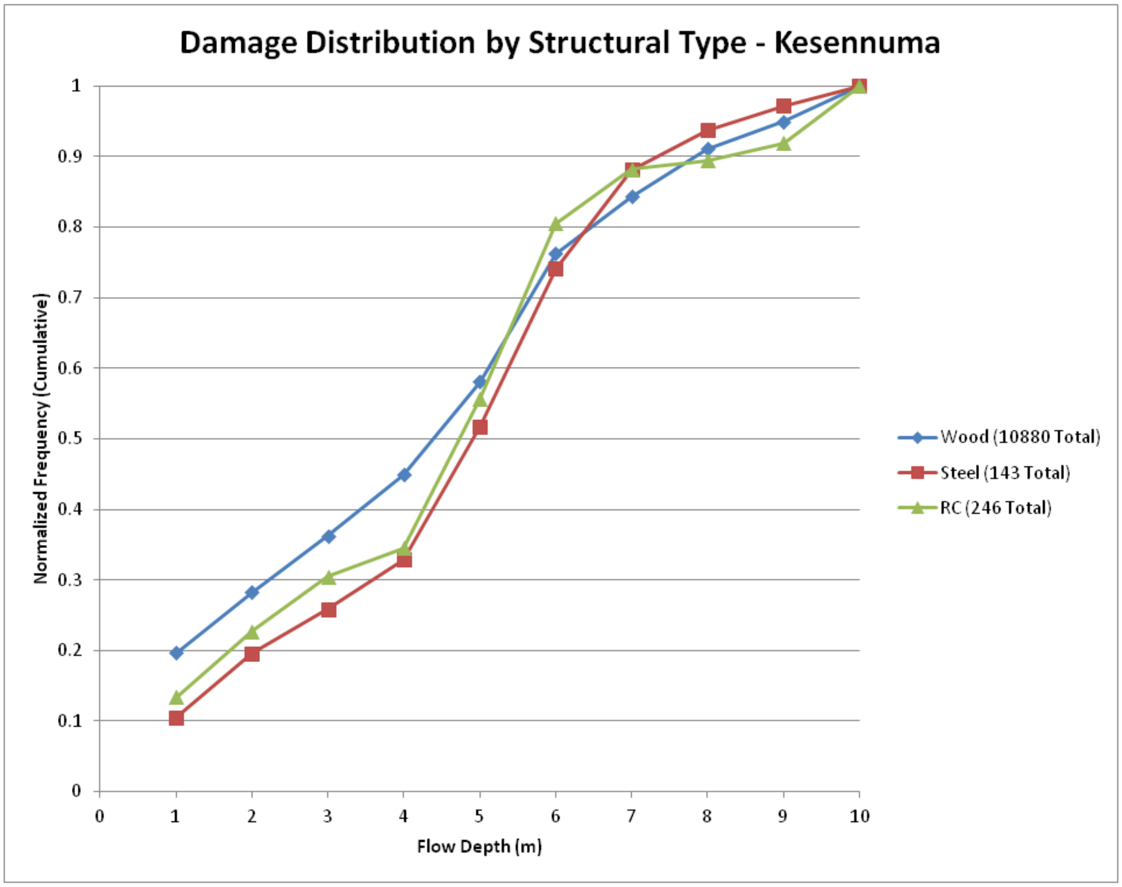
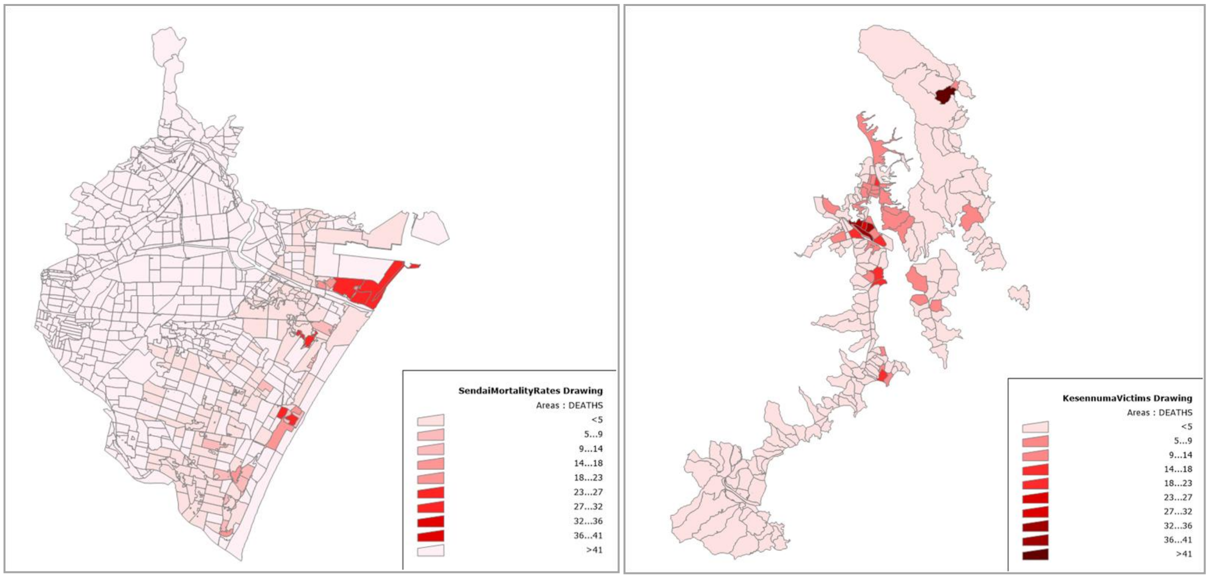


Figure 11: Damage Distributions by Structural Type for Kesennuma (Study Area only)

For Kesennuma, the damage trends appear to be more in line with expectations, i.e., damage rates are highest for wood-frame construction. The range of flow depths for a median damage ratio (50%) is 4.3 meters (wood frame) to about 5 meters for steel. For Sendai, the range is from 3 (steel) to 4.3 (wood frame).

2.2.3 Mortality Rates

Victim statistics for both Sendai and Kesennuma are given on a per block ("ban") basis. A block designation is used for postal services and appears to have no direct relation to population or area. The population and number of deaths per block are given in both a database and GIS format (Sendai data also discloses the population on a household level). Figure 12 shows number of deaths on a block level for Sendai and Kesennuma. The darker zones reflect higher mortality numbers per zone.



Sendai **Kesennuma**

Figure 12: Map of Deaths by Block

According to the government database, 704 people were killed in Sendai during the earthquake and tsunami and over 1,040 people died in Kesennuma. 26 people are still missing in Sendai; 240 are unaccounted for in Kesennuma. Table 9 shows important statistics for areas in Sendai and Kesennuma which suffered the highest number of deaths. The average mortality rate in Sendai for the top ten blocks (highest number of deaths) is 0.05 or five deaths per 100 occupants. The average flow depth associated with these blocks in Sendai is 4.8 meters. The average mortality rate in Kesennuma for the top ten blocks is 0.07 or about 7 deaths per 100 occupants. The average flow depth in Kesennuma for these blocks is 5.5 meters.

Table 9: Block Areas in Sendai and Kesennuma with Highest Number of Deaths

City	# Deaths	Total Population	Mortality Rate	Ave. Flow Depth (m)	# Destroyed Buildings	Total Building
Sendai	44	612	0.07	4.2	283	303
Sendai	31	301	0.01	4.1	149	204
Sendai	31	460	0.01	4.3	241	244
Sendai	29	399	0.07	6.9	263	264
Sendai	27	381	0.07	4.2	323	323
Sendai	23	729	0.03	4.5	488	502
Sendai	23	268	0.09	6.1	170	171
Sendai	21	257	0.08	4.6	223	223
Sendai	18	273	0.07	4.0	133	203
Sendai	17	525	0.03	4.6	229	234
Kesennuma	45	201	0.22	3.8	106	113
Kesennuma	38	886	0.04	3.3	404	483
Kesennuma	38	1200	0.03	4.6	517	533

City	# Deaths	Total Population	Mortality Rate	Ave. Flow Depth (m)	# Destroyed Buildings	Total Building
Kesennuma	32	443	0.07	5.7	328	341
Kesennuma	28	301	0.09	4.9	199	222
Kesennuma	20	181	0.11	7.1	176	176
Kesennuma	19	1270	0.01	2.8	470	519
Kesennuma	19	396	0.05	4.9	207	214
Kesennuma	18	786	0.02	9.6	478	487
Kesennuma	16	304	0.05	8.6	217	220

Figures 12 and 14 show distributions of mortality rate (number of deaths per total population block) by flow depth for Sendai and Kesennuma, respectively. Note that the figures show calculated mortality rates for every block in these areas, i.e., blocks that reported no deaths appear as "zero" points on the x axis (flow depths).

Table 10 shows average flow depths for Sendai and Kesennuma for different mortality rate thresholds, i.e., an examination of flow depths where no deaths were reported, where mortality rates were greater than zero, and where mortality rates were reported to be relatively high (greater than 0.1). The table suggests that flow depth is a key indicator of mortality rate and that impact of the tsunami was greater in Kesennuma than in Sendai.

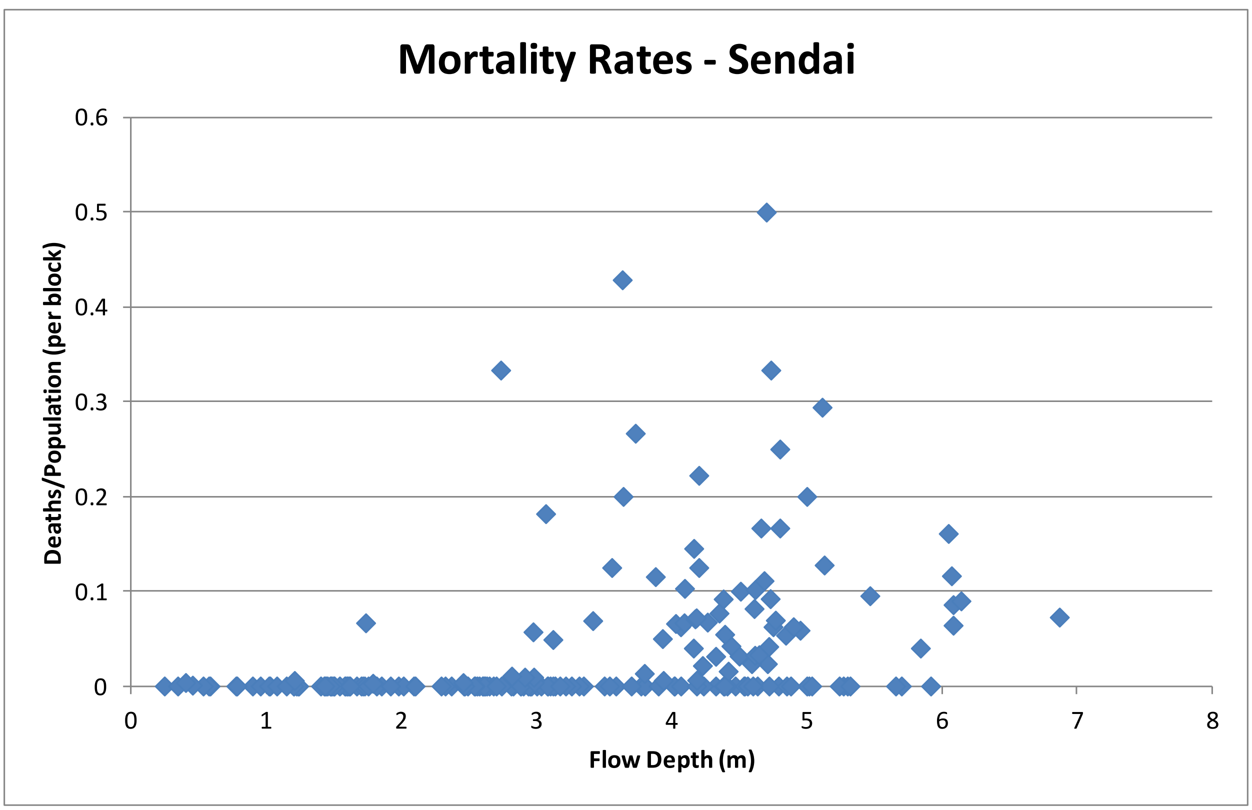


Figure 13: Mortality Rates on a Block Level for Sendai

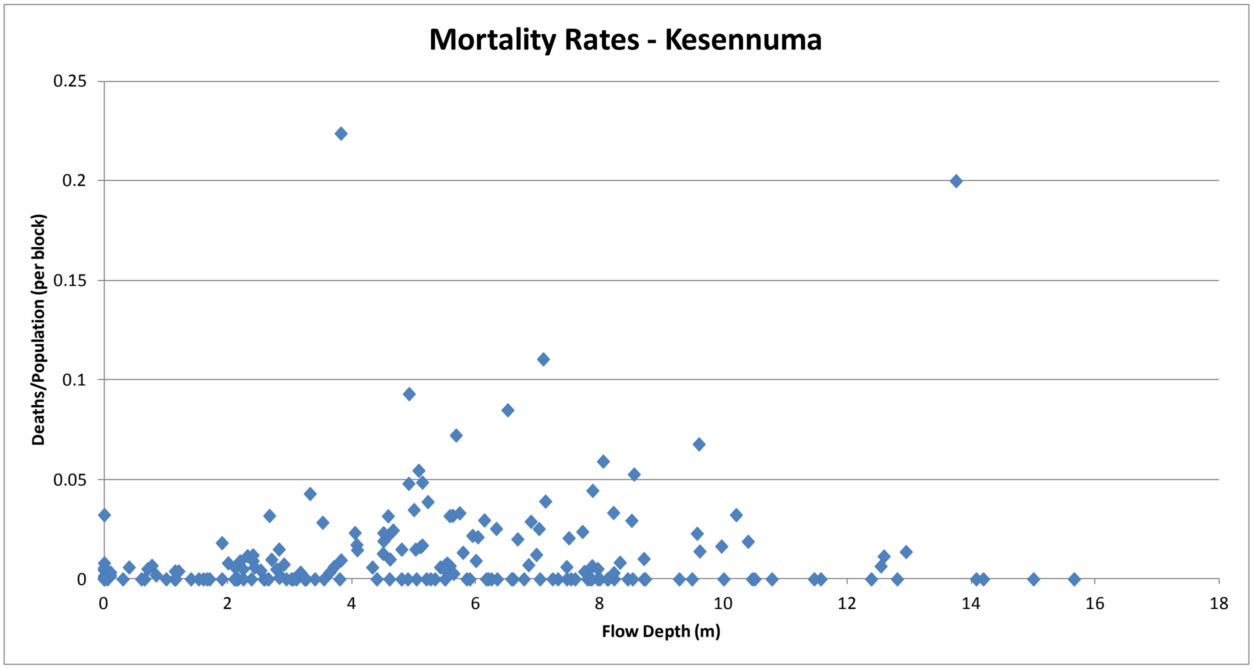


Figure 14: Mortality Rates on a Block Level for Kesennuma

Table 10: Flow Depths versus Different Mortality Rate Thresholds (Deaths/Population on Block Level)

Area	Average Flow Depths for Different Mortality Rate (MR) Thresholds		
	MR equal to Zero (no deaths)	MR greater than Zero	MR greater than 0.1
Sendai	2.2	4.2	4.4
Kesennuma	5.2	4.9	8.2
Combined	3.6	4.2	4.8

2.2.4 Lifelines

The same database used for extracting building damage data was used for evaluating lifeline damage. As mentioned in Section 2.1.4, lifelines were classified into five categories: gas, ports, roads, sewage and water supply. For each lifeline system, there were a number of components listed with damage data. Some datasets were in useful formats, i.e., point facilities with varying amounts of attribute information. In other cases, GIS files showing linear features without much description. In general, data were available only for those lifeline systems and components that experienced significant levels of damage. Unfortunately, data on total number of lifeline components whether damaged or not are not available for any lifeline system. Therefore, normalizing damage information into rates or percentages is not possible at this time.

2.2.4.1 Lifeline Damage States

Three different lifeline damage states were documented in the MLIT database. These damage states were designated and defined as "large" (destroyed), "moderate" (partially damaged with some parts not functioning) and "small" (minor damage with no problems regarding functionality). In order to translate the damage data to states that could be compared to HAZUS output, the development team assigned equivalent HAZUS categories to the Japanese descriptions. These are provided in Table 11.

Table 11: Translation of Japanese Damage States to HAZUS Damage Categories

Japanese Level	Japanese description of damage	Equivalent HAZUS category
3	Small	Slight/None
2	Moderate	Moderate
1	Large	Extensive/Complete

Table 12 contains a summary of damage assignments for all lifeline components considered in the current analysis. Listed in the table are: ID number, city (Sendai, Kesennuma), lifeline system (e.g., gas, sewage. etc.), flow depth (m), damage level (as defined by the MLIT database), damage level (as assigned by project team based on an evaluation of aerial and ground photo data), and contents damage (based on Japanese assignments). Contents damage is more of a description rather than an actual assignment of damage states. In some cases, it is not clear what the damage description refers to, e.g., outflow[1]. The assumption is that most descriptions refer to damage to equipment rather than the non-structural elements of buildings.

In many cases, damage assignments by the project team differ from those contained in the MLIT database. In many of these cases, the MLIT damage assignments were downgraded to lower damage levels. For example, a facility identified as complete by the MLIT data was re-defined as moderate by the development team. The reason for these re-assignments was that when the images (aerial and/or ground photo) for these facilities were examined, especially at time periods months after the earthquake, the facilities were still standing and/or there was clear evidence that the facility was being repaired. Appendix A contains aerial and/or ground photos of each of the facilities listed in Table 12. Perhaps the discrepancies can be explained by the extent of damage to the equipment contained in these facilities. That is, if the equipment were classified as unusable the facility was assigned a "complete" damage level. In order to completely understand the basis for the MLIT damage assignments, in depth interviews may be necessary. Unfortunately, it is not possible to perform these interviews in the current study because of time and resource limitations.

[1] Subsequent to the first submittal of this report, the project team went back and requested a more contextual translation of the term "outflow." According to Professor Yamazaki, the Japanese symbol used for "outflow" refers to large leak or break, and is generally used for pipelines and ducts.

Most of the data in Table 12 is associated with the performance of lifeline components in Kesennuma. This is not unexpected as much of the area analyzed in Kesennuma is industrial, i.e., associated with port operations. Figure 15 and figure 16 show damage states versus flow depths for lifeline facilities in Sendai and Kesennuma, respectively. Damage states are described as follows: 3 – extensive/complete, 2 – moderate, and 1 – slight/none. For this listing, the project team reassignments of damage state were used. The plots suggest a rough dependence on flow depth; a more detailed analysis could indicate that flow velocity must also be considered to better define damage state trends.

Table 12: Summary of Lifeline Component Performance

ID	City	Utility	Component Type	Flow Depth (m)	Damage Level (MLIT)	Damage Level (Re-assigned)	Contents and/or Equipment Damage (Interpreted from Original Japanese Translation)
1	Sendai	Gas	Manufacturing Facility	1.6	**Large**	**Moderate**	**Totally destroyed**
2	Sendai	Sewer	Treatment Plant	4.4	Large	Extensive or Complete (E/C)	Totally destroyed
3	Sendai	Sewer	Pump Facility	4.8	**Large**	**Moderate**	**Totally destroyed**
4	Sendai	Sewer	Pump Facility	4.9	**Large**	**Moderate**	**Totally destroyed**
5	Sendai	Sewer	Pump Facility	2.1	**Large**	**Moderate**	**Totally destroyed**
6	Sendai	Sewer	Pump Facility	1.6	**Large**	**Moderate**	**Totally destroyed**
7	Sendai	Water	Specialty	4.6	**Moderate**	**E/C**	**Totally destroyed**
8	Sendai	Water	Specialty	4.4	**Moderate**	**E/C**	**Totally destroyed**
9	Sendai	Water	Specialty	2	Large	E/C	Outflow
10	Kesennuma	Gas	Power Distribution	8.3	Large	E/C	Outflow
11	Kesennuma	Gas	Power Distribution	0*	Moderate	Moderate	Damaged but repairable
12	Kesennuma	Gas	Power Distribution	5.4	Large	E/C	Outflow
13	Kesennuma	Gas	Storage Facility	11.2	Large	E/C	Outflow
14	Kesennuma	Gas	Storage Facility	9.1	**Moderate**	**E/C**	**Damaged but repairable**
15	Kesennuma	Gas	Storage Facility	3	Moderate	Moderate	Damaged but repairable
16	Kesennuma	Gas	Power Distribution	6.1	Large	E/C	Outflow
17	Kesennuma	Gas	Power Distribution	6.9	Large	E/C	Outflow
18	Kesennuma	Gas	Power Distribution	4.6	**Large**	**Moderate**	**Damaged but repairable**
19	Kesennuma	Gas	Power Distribution	3.4	Large	E/C	Outflow
20	Kesennuma	Gas	Power Distribution	0.6	Moderate	Moderate	Damaged but repairable
21	Kesennuma	Gas	Power Distribution	2.3	Moderate	Moderate	Damaged but repairable
22	Kesennuma	Gas	Manufacturing Facility	2.0	Moderate	Moderate	Damaged but repairable

ID	City	Utility	Component Type	Flow Depth (m)	Damage Level (MLIT)	Damage Level (Re-assigned)	Contents and/or Equipment Damage (Interpreted from Original Japanese Translation)
23	Kesennuma	Sewer	Pump Facility	7.6	Large	E/C	**Totally destroyed**
24	Kesennuma	Sewer	Pump Facility	10	**Moderate**	**E/C**	**Totally destroyed**
25	Kesennuma	Sewer	Pump Facility	9.8	Large	E/C	Outflow
26	Kesennuma	Sewer	Pump Facility	0*	Moderate	n/a	Damaged but repairable
27	Kesennuma	Sewer	Treatment Plant	8.1	**Large**	**Moderate**	**Damaged but repairable**
28	Kesennuma	Sewer	Pump Facility	8.3	**Large**	**Moderate**	**Damaged but repairable**
29	Kesennuma	Sewer	Treatment Plant	5.9	Large	E/C	Totally destroyed
30	Kesennuma	Sewer	Pump Facility	5.3	**Large**	**Moderate**	**Damaged but repairable**
31	Kesennuma	Sewer	Pump Facility	6.9	**Large**	**Moderate**	**Damaged but repairable**
32	Kesennuma	Sewer	Pump Facility	9.9	**Large**	**Moderate**	**Damaged but repairable**
33	Kesennuma	Sewer	Treatment Plant	3	**Large**	**Moderate**	**Damaged but repairable**
34	Kesennuma	Sewer	Treatment Plant	7	Moderate	Moderate	Totally destroyed
35	Kesennuma	Sewer	Treatment Plant	10.5	**Large**	**Moderate**	**Damaged but repairable**
36	Kesennuma	Sewer	Pump Facility	3.3	**Moderate**	**E/C**	**Damaged but repairable**
37	Kesennuma	Sewer	Pump Facility	6.2	Large	E/C	Damaged but repairable
38	Kesennuma	Water	Intake Facility	0*	Moderate	Moderate	Damaged but repairable
39	Kesennuma	Water	Water Treatment Facility	10.7	Moderate	Moderate	Damaged but repairable
40	Kesennuma	Water	Specialty	8.5	Moderate	n/a	Damaged but repairable
41	Kesennuma	Water	Water Treatment Facility	11.8	Large	E/C	Outflow
42	Kesennuma	Water	Specialty	2.8	**Large**	**Moderate**	**Damaged but repairable**

*Note: Damage states that were re-defined by the project team are highlighted in **bold**. Also, zero flow depths for some facilities are a result of assigning grid-based or average flow depths to specific sites.

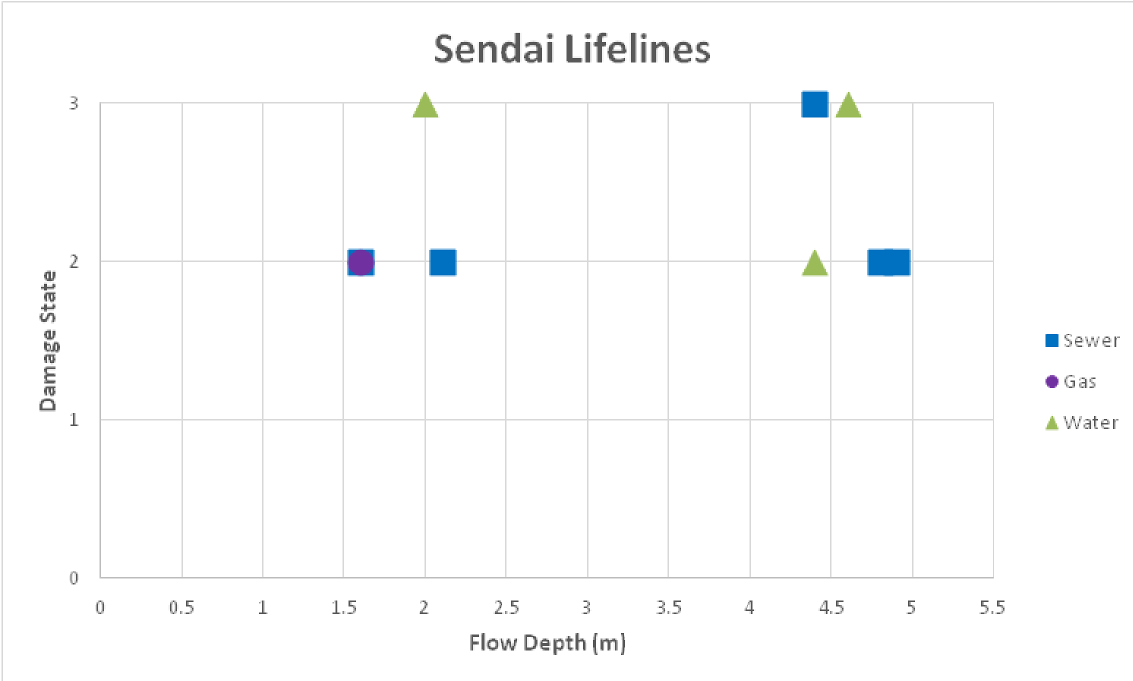


Figure 15: Simple Plot of Damage State versus Flow Depth (m) for Sewage, Gas and Water Lifeline Components in Sendai (Damage State 3 – Extensive/Complete; 2 – Moderate; 1 – Slight/None)

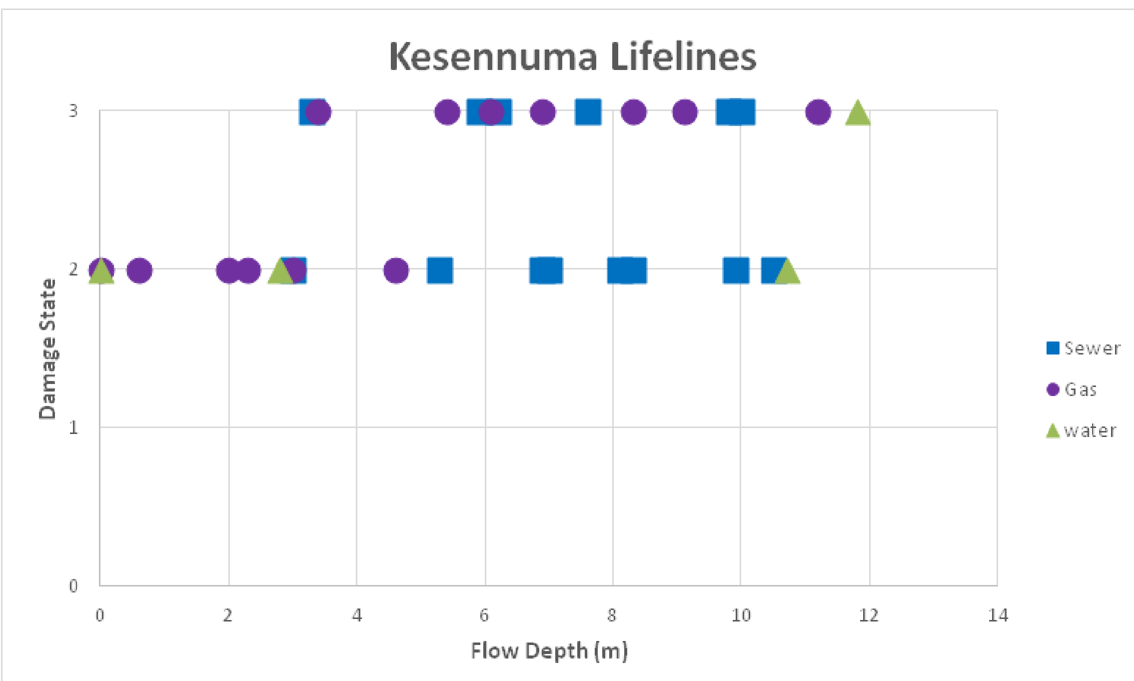


Figure 16: Simple Plot of Damage State versus Flow Depth (m) for Sewage, Gas and Water Lifeline Components in Kesennuma (Damage State 1 – Extensive/Complete; 2 – Moderate; 1 – Slight/None)
Note: Damage at flow depths of zero likely due to grid-based flow depth assignments as opposed to site-specific measurements which were not available from the MLIT database

2.2.5 Transportation

Damage data for ports, bridges and roadways are also contained in the MLIT database. However, as in the case of lifelines, only data on damaged facilities is provided in that database, i.e., inventory information on all exposed facilities whether damaged or not is not available. Because of this, the estimation of damage rates is not possible. A recommendation coming out of this study is to explore in more detail with Japanese government agencies (local and regional) the availability of inventory information or data. Another possible approach would be to use pre-event satellite imagery or Google Earth to manually measure the number of road miles or the number of bridges. However, the latter approach is expected to be very time-consuming and beyond the scope of the present project.

2.2.5.1 Ports

Figure 17 shows recorded damage to port facilities in Sendai. Three damage states are noted in the figure: extensive/complete (red), moderate (orange) and none/slight (yellow). As noted earlier in Table 11, in order to properly match the Japanese-defined damage states to those used in HAZUS, the "Extensive" and "Complete" damage states (in HAZUS) were combined. Complete damage noted in the figure is associated with wharf facilities.

Figure 18 provides a delineation of damage for port facilities in Kesennuma. Unlike Sendai, damage is spread through the region that surrounds the port of Kesennuma.

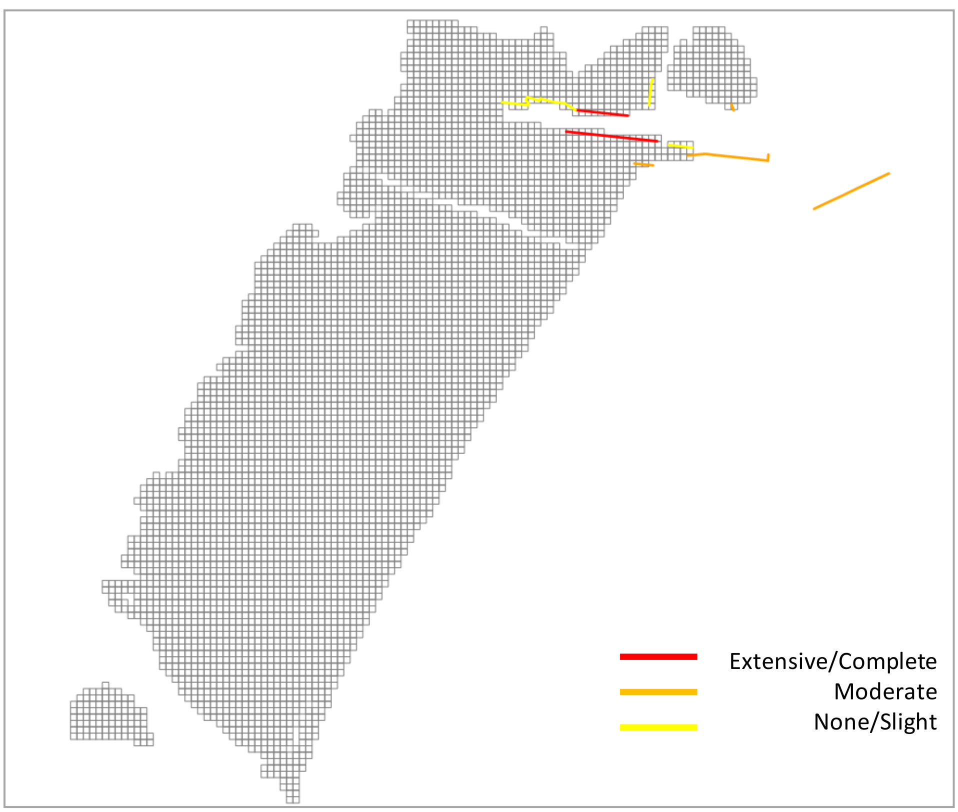


Figure 17: Delineation of Damage to Port Facilities in Sendai

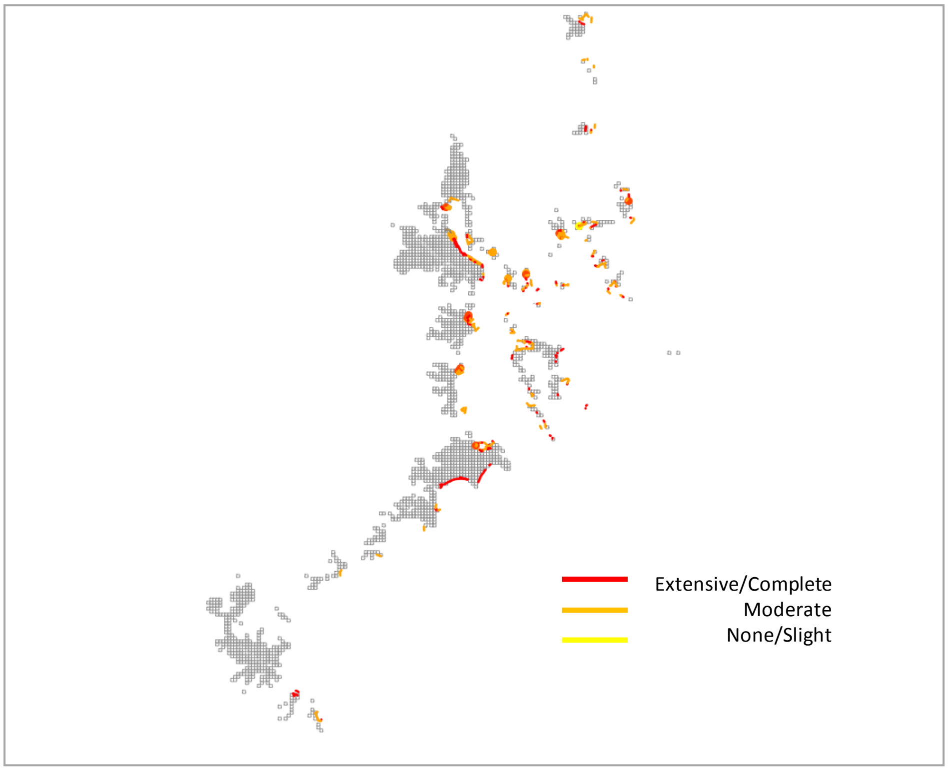


Figure 18: Delineation of Damage to Port Facilities in Kesennuma

2.2.5.2 Roadways

Roadway damage in the two study regions is illustrated in Figures 19 and 20. Unsurprisingly, roadway damage is highest in areas closest to the coastline for both regions. Although roadways are assigned different damage states in the MLIT database, it is not entirely clear what type of effects or damage are associated with each state. A possible task following this study is to obtain clarification of from Japanese investigators on the damage criteria used to assign damage states to different roadway systems. Damage could be defined based on actual pavement damage from water undermining the soil beneath the pavement, or from debris that is deposited on the roadway from incoming tsunami waves. At this point, not enough detail is provided in the MLIT database to discern these different effects. Table 13 provides a high-level summary of roadway damage by damage class.

Table 13: Roadway Damage for Study Areas

Damage State	Sendai (km)	Kesennuma (km)
Extensive/Complete	9.9	40.8
Moderate	34.1	19.8
None/Slight	40.4	2.3
Total	84.4	63.9

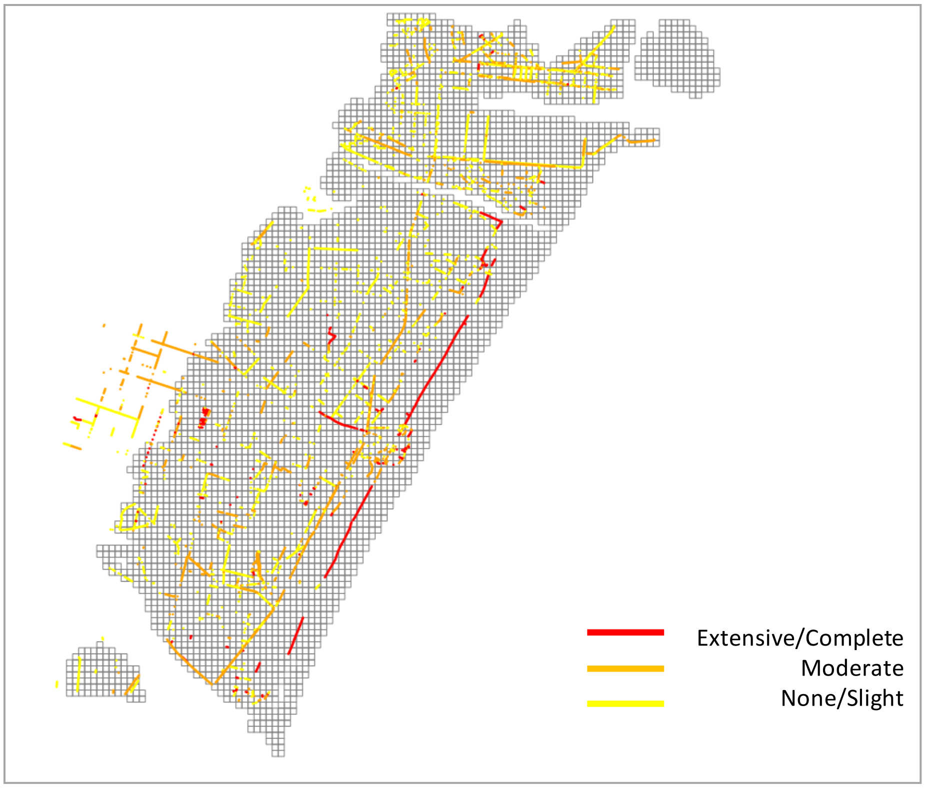


Figure 19: Roadway Damage in Sendai

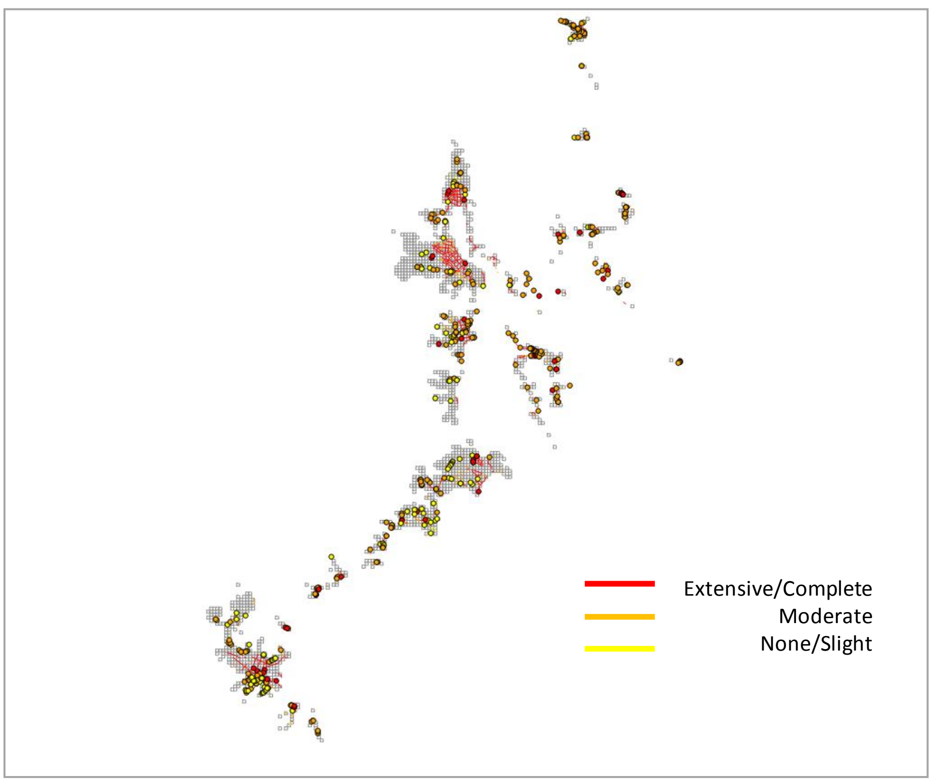


Figure 20: Roadway Damage in Kesennuma

2.2.5.3 Bridges

Table 14 contains damage assignments for individual bridges for both Sendai and Kesennuma. As in the case for other lifelines, three damage states are used: slight/none, moderate, and extensive/complete. Furthermore, the table breaks down this data by flow depth. As noted in the table, data for Sendai are provided up to the maximum flow depth recorded, i.e., about 10 meters. For Kesennuma, data are given up to 16 meters. In total, 105 bridges in Sendai suffered some level of damage with about 80 percent falling in the "complete" damage state category. In Kesennuma, only 72 bridges were identified as being damaged with roughly 65 percent in the "complete" category.

Table 14: Bridge Damage Data in Sendai and Kesennuma

Flow Depth (m)	Damage States - Sendai				Damage States - Kesennuma			
	Slight/None	Moderate	Extensive/ Complete	Subtotal	Slight/None	Moderate	Extensive/ Complete	Subtotal
1	0	0	3	3	4	1	6	11
2	0	0	0	0	0	0	3	3
3	0	1	11	12	0	0	3	3
4	1	0	10	11	1	0	4	5
5	9	3	30	42	1	0	1	2
6	3	4	17	24	0	1	1	2
7	1	0	10	11	1	0	6	7
8	0	0	1	1	0	0	2	2
9	0	0	0	0	0	0	1	1
10	0	1	0	1	1	0	4	5
11	-	-	-	0	3	0	6	9
12	-	-	-	0	0	1	5	6
13	-	-	-	0	1	1	1	3
14	-	-	-	0	0	1	2	3
15	-	-	-	0	4	1	2	7
16	-	-	-	0	3	0	0	3
Total	14	9	82	105	19	6	47	72

Figure 21 shows a cumulative plot of number of bridges as a function of flow depth for each damage state. The figure includes data from both Sendai and Kesennuma. All damage state curves ramp up quickly around the 4 to 6 meter flow depth range. This implies that this range represents a key threshold, i.e., significant damage begins to occur at 4 meters flow depth. What is not considered in this simple assessment is the height of each bridge deck (a key parameter in the HAZUS Tsunami methodology for bridges). A more thorough study of this damage data is needed in order to fully understand whether these trends can be replicated by a standardized methodology. Recommendations for additional analyses are given in the last section of this report.

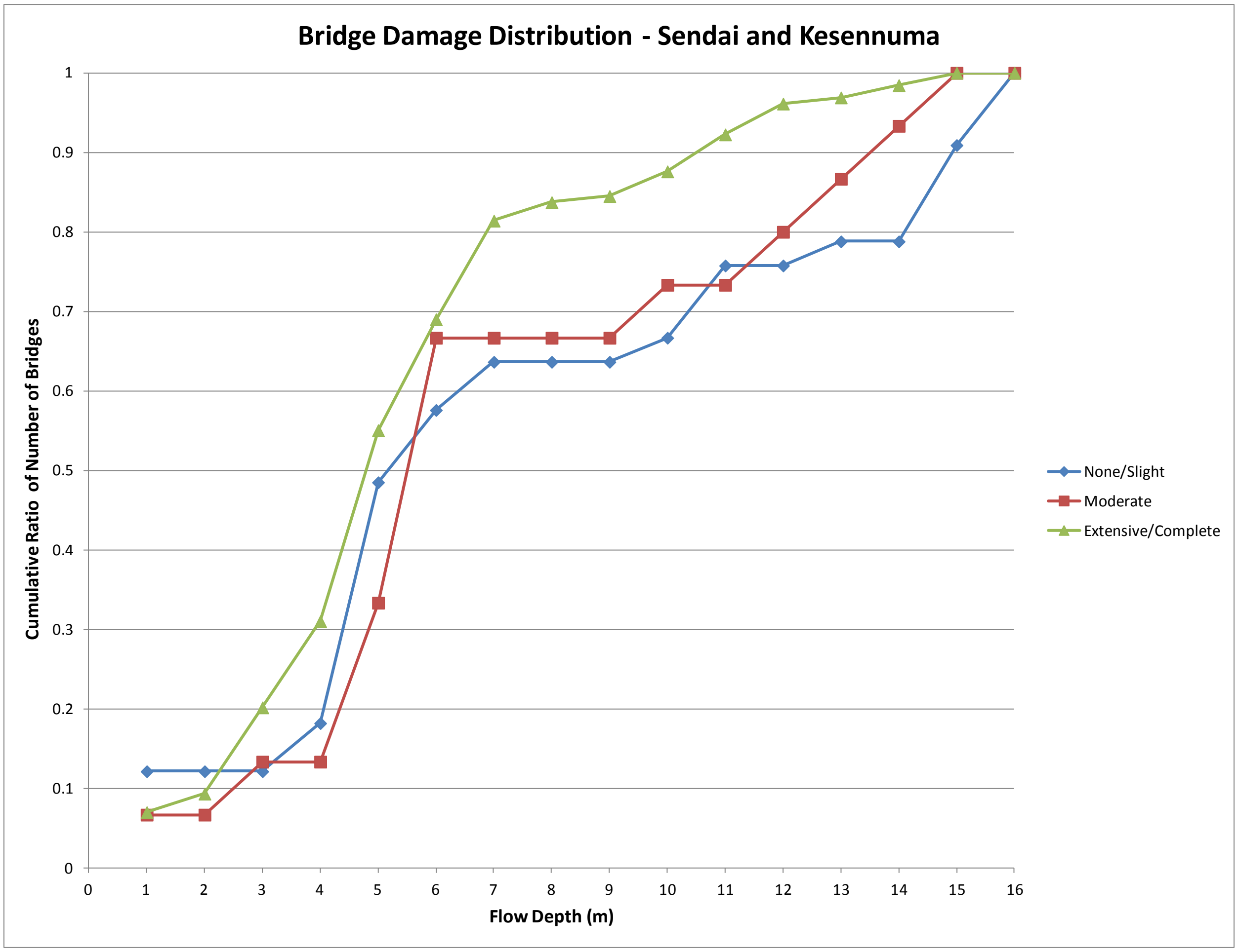


Figure 21: Plot of Cumulative Ratio of Number of Bridges as a Function of Flow Depth (m) for Damage States Slight/None, Moderate and Extensive/Complete

2.3 Comparison with HAZUS Modeled Results

In this section, preliminary comparisons are made between the HAZUS Tsunami modeled results and the MLIT data presented in the previous section. For lifelines, comparisons are made for only a few lifeline component types since data on the Tohoku earthquake are provided only for facilities with some level of damage. That is, facilities that suffered no damage are not included in the MLIT database. Therefore, normalized estimates of damage that could lead to damage probabilities are not possible. No comparisons are provided for casualty or mortality estimates.

2.3.1 Buildings

Tables 15 and 16 show the results of the damage calculations for Sendai and Kesennuma, respectively, using the newly-developed HAZUS-Tsunami methodology. To estimate the expected level of damage at each flow depth, the following set of flux values were used:

Flow Depth (m)	Flux (ft^3/sec^2)
0 - 1	100
1 – 2	200
2 – 3	500
3 – 4	1000
4 – 5	1300
5 – 6	1600
6 – 8	2000
8 – 10	3000
10 – 12	5000
12+	10000

Furthermore, it was assumed that 85% of the buildings were of wood construction, 10% of steel, and 5% of concrete.

Table 15: Modeled Results for Sendai

Damage State	Flow Depth (meters)						
	0-2	2-4	4-6	6-8	8-10	>10	Total
Extensive	1	27	43	6	0	0	77
Complete	404	2,950	3,708	569	26	2	7659
Subtotal	405	2,977	3,751	575	26	2	7,736

Table 16: Modeled Results for Kesennuma

Damage State	Flow Depth (meters)					
	0-3	3-6	6-9	9-12	12-15	Total
Extensive	6	65	30	8	0	109
Complete	1,258	5,727	3127	1730	790	12,632
Subtotal	1,264	5,792	3,157	1,738	790	12,741

A comparison of the results above with actual observations of damage in Sendai and Kesennuma in the Tohoku earthquake reveals several important findings. The first is that damage in only the “Extensive” and "Complete" damage states is predicted by the HAZUS model, i.e., no moderate or slight damage is estimated. This suggests that the HAZUS damage function works primarily as a "step" function in its current state. The second finding is that the total number of buildings estimated to have *complete* and *extensive* damage by HAZUS reasonably close to the actual numbers observed for both study areas, i.e., for Sendai, 7736 predicted versus 6,961 observed; for Kesennuma, 12,741 predicted versus 17,667 observed. Thus, the HAZUS model scales well with the Tohoku data.

Figure 22 shows a comparison (HAZUS versus Actual) of the normalized distribution of damaged buildings for extensive and complete damage for Sendai. For both extensive and complete damage, both datasets show a median flow depth of about 4 to 6 meters.

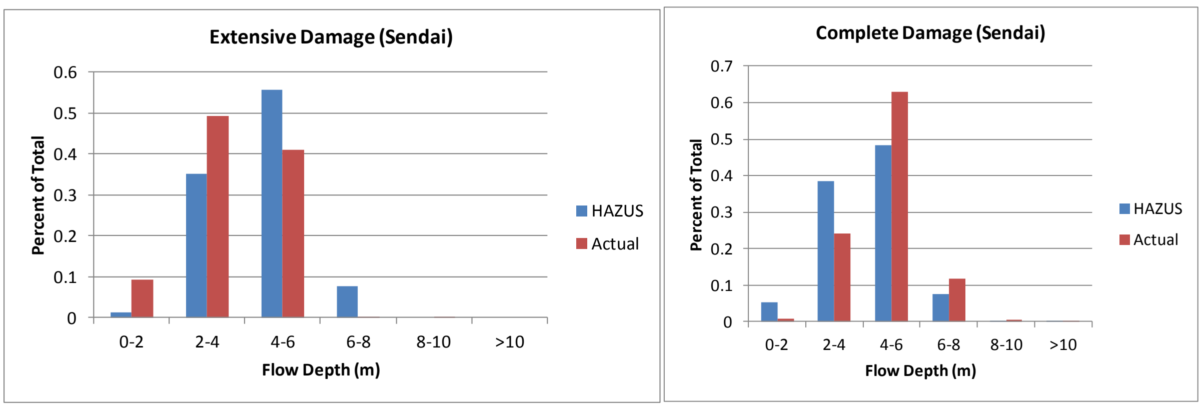


Figure 22: Comparison of Predicted versus Actual Observations of Building Damage for Sendai

Figure 23 provides a similar comparison between predicted versus actual observed building damage for Kesennuma. In this comparison, the median flow depth for extensive damage is significantly different from the HAZUS prediction producing a median flow depth of about 3 meters as compared to about 1 to 2 meters from the MLIT data. For complete damage, the median values of flow depth are more comparable with both around 3 to 6 meters.

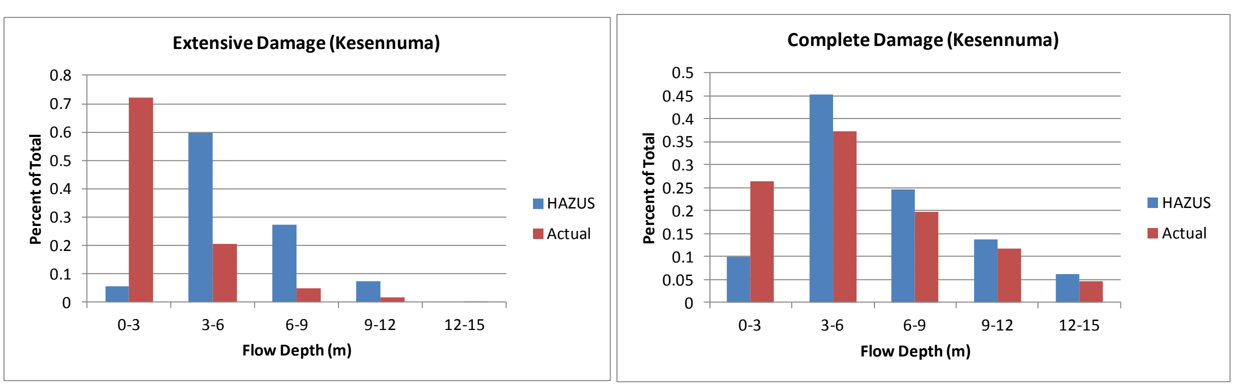


Figure 23: Comparison of Predicted versus Actual Observations of Building Damage for Kesennuma

It should be noted that these comparisons are considered very preliminary in that much more data from the Tohoku earthquake could be incorporated in this benchmarking. At least a half dozen more cities along the Northeastern coast of Japan could be added to the HAZUS benchmarking dataset.

2.3.2 Bridges

Japan and the U.S. use similar details for bridge design of superstructures (unlike for substructures), and since most tsunami damage is related to loss-of-superstructure, they are considered equally tsunami-resistant, or equally vulnerable as the case may be. According to Professor Ian Buckle (University of Nevada at Reno), bridges that had integral superstructures (girders monolithic with substructures) did very well, whereas those with non-integral superstructures (girders connected through bearings to their substructures) were more likely to be unseated. And since Japan builds more of the second type of bridge than the first, and the reverse is true on the west coast, it could be argued that U.S. bridges are less vulnerable, overall. Currently, Professor Buckle is studying this aspect of bridge performance in an FHWA-sponsored project.

The fragility curves generated from the HAZUS model for all damage states are shown in Figure 24 (note that the inundation or flow depth scale has been transformed into feet above base). The assumptions used in generating these curves include: bridge deck height equal to 20 feet, high velocity flow, and no debris impact. Also plotted on the figure are the "extensive/complete" damage points from the MLIT database, see Table 14. In Figure 24, the MLIT data from Sendai and Kesennuma have been combined for a total of 129 bridges. Although the MLIT database does not indicate the total number of bridges that were exposed to flood inundation in our study areas, a paper prepared by researchers in Japan (Maruyama et al., 2013) lists a total of 794 bridges in Miyagi Prefecture (where Sendai and Kesennuma are located) in the area of inundation. The paper also indicates that 102 were either "washed away" or "moved."

In Figure 24, the MLIT data points suggests that the HAZUS fragility model using the parameters given above overestimates the probabilities of experiencing either complete or extensive damage, i.e., the MLIT data points are located to the right of the curves. There could be a variety of reasons why this is the case, however, without performing a thorough sensitivity analysis, it is difficult to identify which parameters or assumptions are responsible for the differences. We know that at best, these comparisons provide a starting point or a benchmark for scaling and that the initial models are the result of expert opinion and not empirical data. Therefore, it is no surprise that we see large differences between the curves and actual data.

In order to proceed with a calibration of the model, we strongly recommend that bridge performance data from other areas affected by the Tohoku earthquake (besides Sendai and Kesennuma) be added to the comparison dataset. In addition, to ensure that the damage totals are normalized to the entire set of bridges affected by inundation, we recommend that bridge inventory data for each study area be sought from the appropriate government agency. Although it is possible to identify bridges from remote sensing imagery (this is especially true for bridges crossing rivers or water bodies), it may be difficult to identify all bridges especially if there are small and/or located in densely built-up areas.

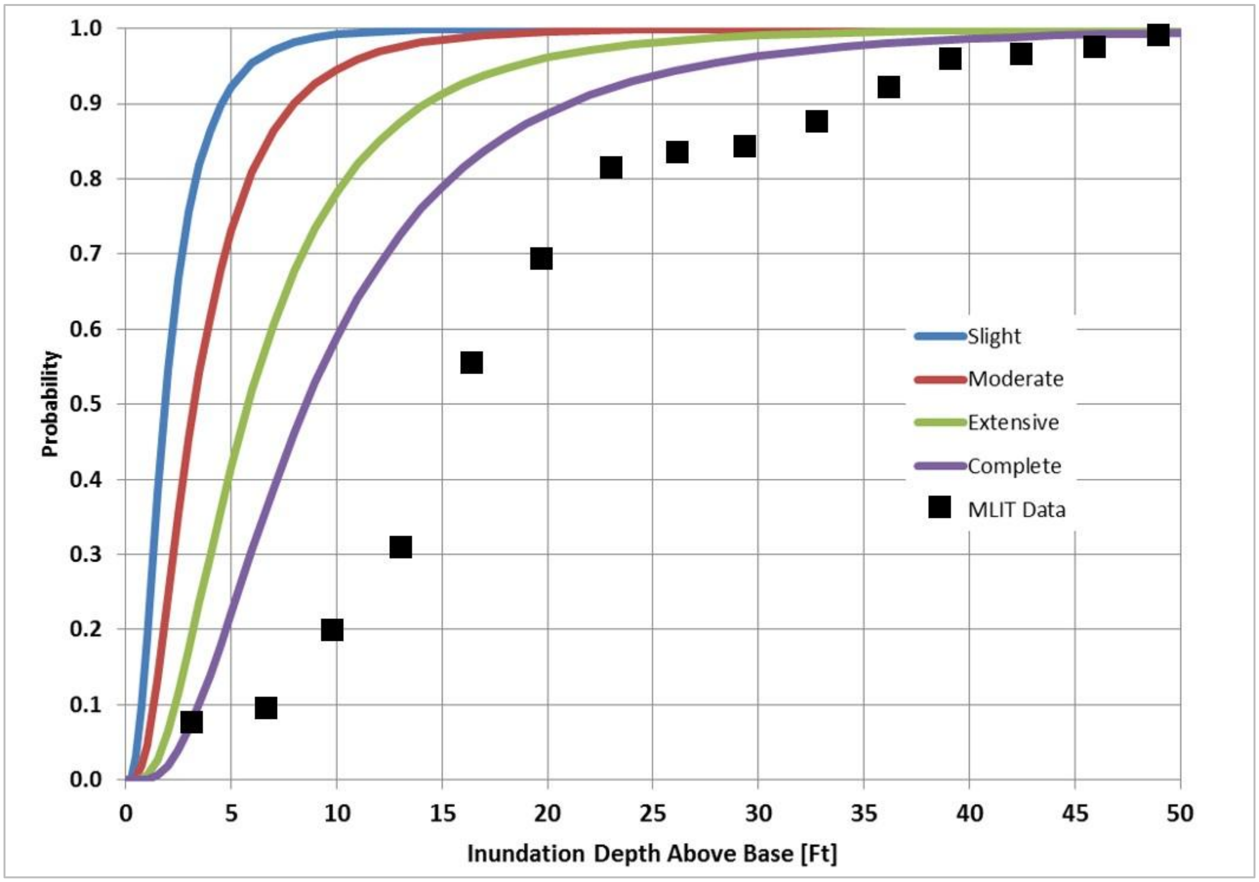


Figure 24: A Comparison of HAZUS-generated fragilities with Actual Data from the Tohoku earthquake (Note: MLIT data points only for Extensive and Complete damage)

2.3.3 Lifelines

The 2011 Tohoku earthquake and tsunami provides a rich data set for benchmarking many of the HAZUS tsunami fragilities for lifelines. As a first attempt to compare the Japanese data from the Tohoku event with HAZUS modeled results, we took damage data from the MLIT survey for several sites, for selected component types. For sewer pump or lift stations, the data included flow depths from 5 feet to over 30 feet, and flow velocities that were characterized as "low peak flow[2]." From the cases we examined for sewage pump/lift stations, the vast majority of plants were classified as having "Complete" damage, as defined by MLIT survey. A similar observation is made for treatment facilities (both water and sewage)

[2] Note that a more appropriate definition of flow rate for this example should be high velocity. However, we know from the bridge example above that not only do the velocity parameters need to be adjusted but other parameters in the analytical model must be adjusted. However, before performing this calibration, it would make more sense to collect as much data as possible (including from other areas in Japan affected by the earthquake and tsunami) and then perform the calibrations. Therefore, the examples that are presented above have essentially been unchanged since the first submittal of this report.

and water pump stations.

As discussed in Section 2.2.4.1 and Table 11, the project team re-classified many of these damage assignments based on post-earthquake aerial and ground photos. As explained in Section 2.2.4.1, it appears that damage to contents and equipment led to many of the facilities being classified as completely destroyed; however a review of post-earthquake photos at various time periods clearly shows that a number of these facilities were being repaired as opposed to being rebuilt.

In comparing the results between HAZUS fragility output and the MLIT damage data, the project team considered various uses of the data in Table 11. Initially, the project team considered using the "re-interpreted" damage states, as determined through remote sensing analysis and/or a review of ground photos; however, it was finally decided to make the comparisons with the original MLIT damage classification. By doing this, the project team was able to assemble a much larger data sample to compare the fragility results to. As in the case for bridges, the project team feels that a comparison of results for "large damage" from the MLIT database with the "extensive/complete" output from the HAZUS fragility curves makes the most sense at this time. In order to parse out the data in finer damage categories, more research and possibly more facilities from other areas affected by the Tohoku earthquake are needed.

Figure 25 shows two fragility curves, one for "Extensive" damage and one for "Complete" damage. The curves are for sewage pump or lift stations. In order to increase the size of the data sample for these comparisons, the project team decided to combine MLIT damage data for sewage and water pump stations, and water and sewage treatment facilities. The project team felt that the type of construction for all of these facilities would be roughly the same (i.e., reinforced-concrete, block buildings, low story) and the type of equipment in these facilities would also be similar (e.g., pumps, pipes, generators, electrical equipment). Appendix A contains aerial and ground photos for all facilities listed in Table 12. In total, 17 sewage/water facilities were included in the comparison. The empirical fragility data are plotted along side of the two HAZUS fragility curves.

A comparison shows that the match between the fragility model output and the MLIT data does not result in a good match. The project team has speculated why this may be the case. One of the obvious possibilities is that the flow or inundation depth associated with each facility may not have been the depth at which extensive or complete damage first began. That is, by plotting the MLIT damage data at the maximum flow depths measured we may be "pushing" the empirical data out too far. In order to investigate this, we have plotted a second set of MLIT data points where we only include damage data with flow depths less than 25 feet (a typical story height for a pump station – see Appendix A). The comparison, shown in Figure 26 shows that the empirical data is roughly in the same probability/flow depth range as the fragility curves for "Extensive" and "Complete" damage but suggests a linear versus exponential trend. It is difficult to conclude which trend or functional form is correct given the limited data sample. We suggest as part of a future study to include damage data from other cities in Japan in order to generate a more robust and perhaps more component-specific dataset for comparison.

An example of the extent and level of work needed for a more complete comparison of fragilities is presented in [Suppasri et al, 2013] where fragilities were constructed based on damage collected for more than 250,000 building structures with recorded inundation depths. The Suppasri et al study does not consider damage from earthquake shaking occurring prior to tsunami inundation, nor does it provide fragilities as a function of flow velocity or debris impact. It is nonetheless a very comprehensive dataset. Such comprehensive fragility relationships would provide an adequate basis for validation of HAZUS tsunami fragilities, and for adjustment to match the data (i.e., calibration).

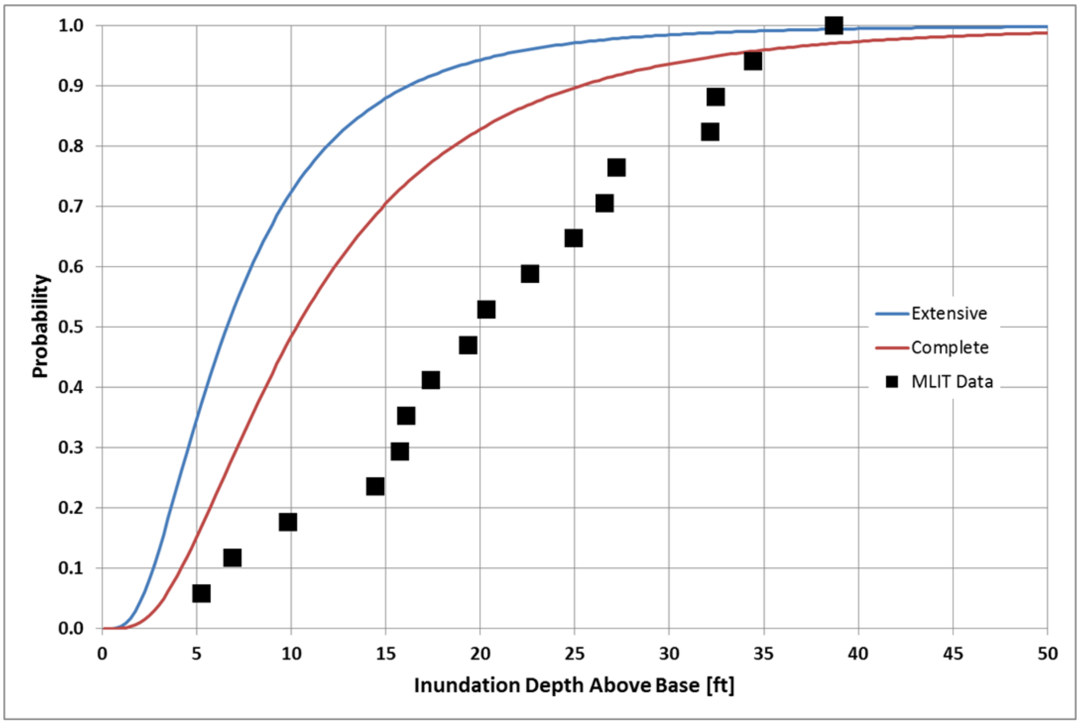


Figure 25: Tsunami Fragility Curve for Sewage/Water Facilities (data points in figure are plots of Tohoku damage data)

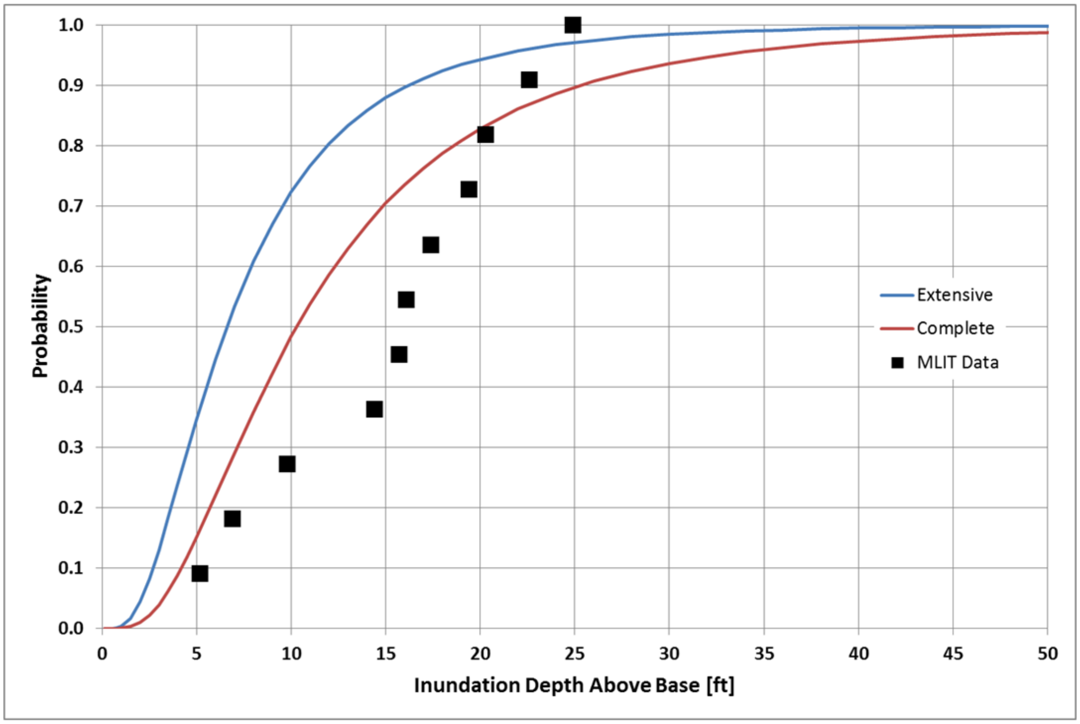


Figure 26: Modified Tsunami Fragility Curve for Sewage/Water Facilities with only MLIT Damage Data having Flow Depths of 25 feet or lower.

Unfortunately, the MLIT data for other lifeline components is very limited and performing any comparisons are likely not to provide useful information to either validate or calibrate the existing fragility functions. We therefore strongly suggest that the damage data from other regions of Japan, which also greatly were affected by the tsunami, be included in more comprehensive analysis of lifeline fragilities.

Another assumption that will need to be addressed is whether the data contained in Table 12 is a summary of all the lifeline facilities that were inundated in Sendai and Kesennuma. If Table 12 only includes facilities that recorded some level of damage, then the damage rates that are presented in Figures 25 and 26 would have to be adjusted, i.e., normalized by the total number of facilities experiencing that flow depth. This would further increase the differences between the HAZUS modeled results and the actual MLIT damage data.

As with the bridge results, the research team strongly suggests that the damage data be augmented with data from other affected regions and that a systematic and thorough calibration of the models be conducted on the larger dataset. In addition, with larger datasets it may be possible to refine the categories of lifeline components and produce individual fragility models for each lifeline system.

2.3.4 Casualties

In an effort to calibrate the HAZUS tsunami casualty model, a total of seven blocks were randomly selected from the two coastal cities (two in Sendai and five from Kesennuma). As mentioned previously in Section 2.2.3, each block contained information regarding population and number of fatalities. What was not available was demographic data for the total population. Therefore an assumption of 30% adult males, 30% females and 40% children was used and a mean evacuation speed of 1.36 m/s was computed with a variance of 0.0464 $(m/s)^2$. This assumption was applied at each block level. See Appendix B for more details on the assumptions used by Harry Yeh in his casualty estimation.

The elevation of the centroid of the block was then extracted, in addition to the elevation and distance to both the 2m inundation contour and inundation boundary (i.e., beyond this boundary, no deaths occur). Given Japan's history and knowledge of tsunamis, a value of 0.1 was used for C_{std}, which is assigned for well prepared communities in the methodology (see HAZUS Tsunami methodology document). Arrival and warning times were estimated to be 30 and 6 minutes and 60 and 25 minutes for Kesennuma and Sendai, respectively. Figure 27 illustrates geographically each of these assumptions for Sendai.

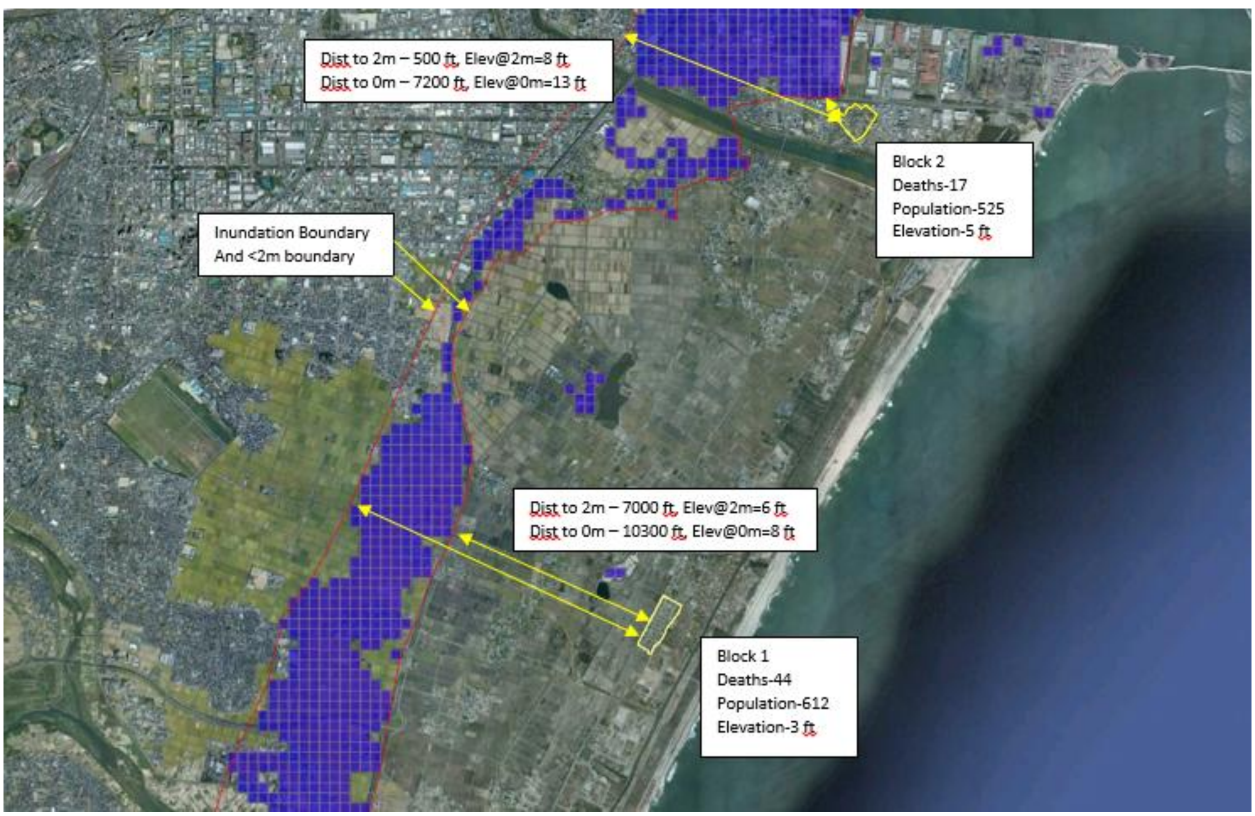


Figure 27: Sendai test blocks with measurements to the 0m and 2m tsunami contour boundaries

The results of the HAZUS mortality model are presented in Table 17. It is important to understand that this preliminary analysis is the start of a calibration effort, and not a model validation. Calculated and actual fatalities can vary significantly from block to block. Assumptions in the HAZUS tsunami variables (tortuosity, evacuation conditions, demographics, etc.) compounded with the assumptions made for evacuation points (0 and 2m contour) can have significant impacts on the results produced by the model. Distances to known evacuation points will have reduced the evacuation times, and ultimately the predicted fatalities.

Table 17: Comparison of Actual and HAZUS Fatality Results

City	Block	Population	Calculated Fatalities	Actual Fatalities
Kesennuma	1	443	5	32
Kesennuma	2	384	55	15
Kesennuma	3	338	16	10
Kesennuma	4	115	0	4
Kesennuma	5	301	1	28
Sendai	1	612	28	44
Sendai	2	525	50	17

To fully calibrate the mortality models, a better understanding of the Japanese MLIT data should first be considered. Knowing exact locations of evacuation zones, and probable evacuation routes can significantly reduce uncertainties in the distance required (both horizontally and vertically (elevation changes)). Also knowing the demographics of the region will give a better understanding of the evacuation speed most likely sustained in both regions. Including more blocks in each region to add to the sample size could also help identify variables that require re-calibration.

3. 1964 Alaska Earthquake – Crescent City

The 1964 Alaska Earthquake occurred on March 27, 1964 with a magnitude of 9.2. The epicenter was located approximately 12 miles north of Prince William Sound and 75 northwest of Anchorage. Approximately 4 hours later, the first of four waves reached the Crescent City shoreline. The first three were reported as small with little to no damage, whereas the fourth wave reached heights of approximately 20 feet and caused significant damage to the ports and surrounding areas. Approximately 289 buildings were destroyed and 12 people were confirmed dead.

3.1 Description of Data for Crescent City

A historical map (Figure 28) obtained from Professor Lori Dengler of Humboldt University shows data from surveys conducted by the U.S. Army Corps of Engineers. Data includes footprints of buildings within the Crescent City Harbor, an identification of destroyed buildings, and mapped tsunami depth contours. A digital form of the map was produced by the project team by geo-referencing and digitizing both the building footprints and flow depth contours. Figure 29 shows the digitized version of the historical map.

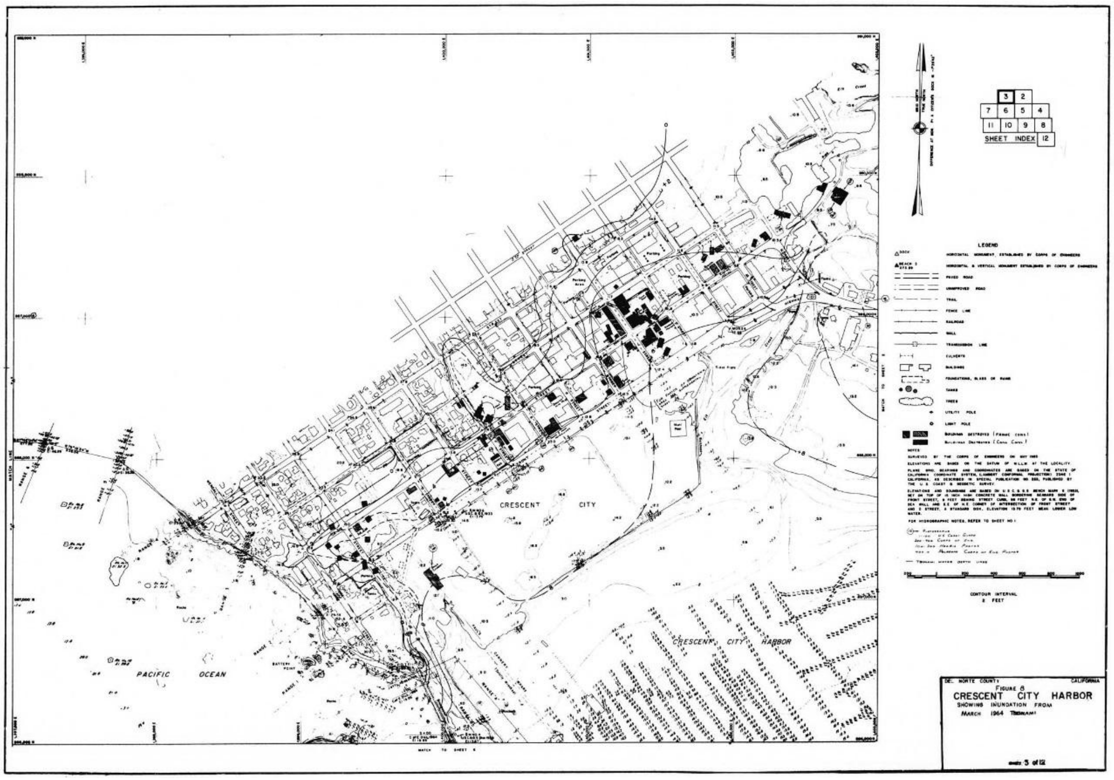


Figure 28: Map of Destroyed Buildings and Tsunami Height Contours (Source: Dengler)

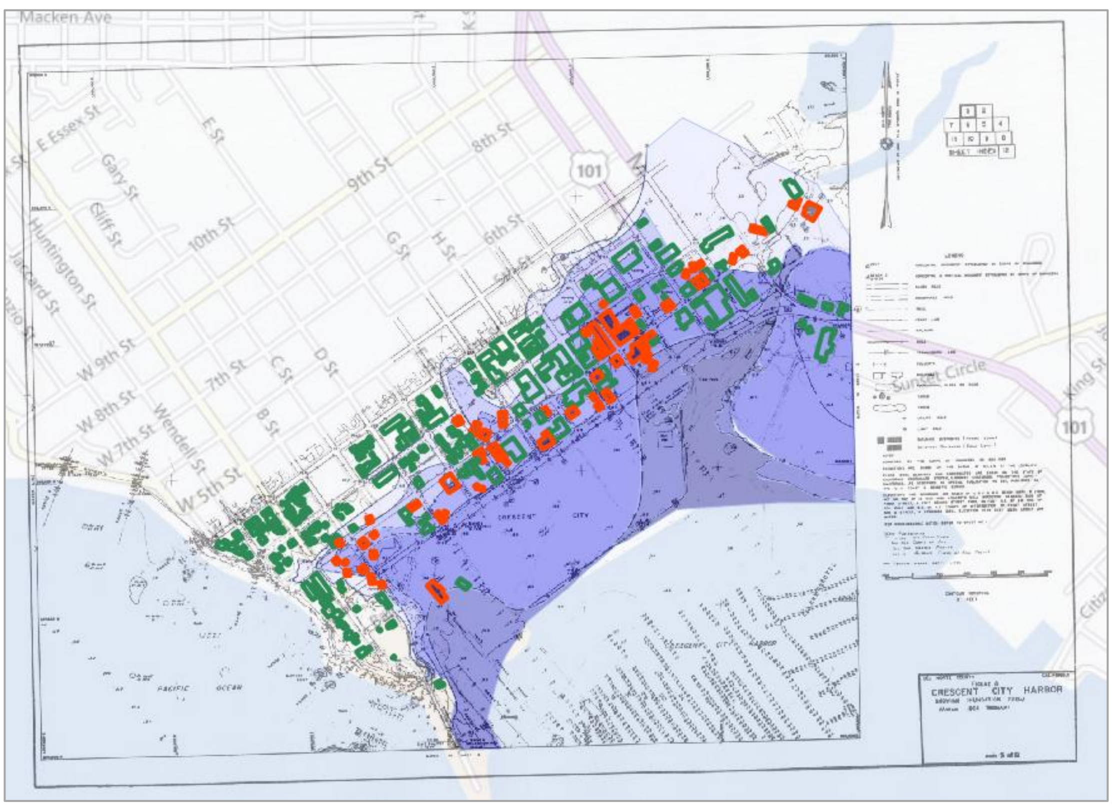


Figure 29: Digitized Version of Historical Map with Footprints and Inundation Lines Digitized, Geo-referenced and Overlaid on Bing Maps. Red outlines delineate destroyed structures.

Table 18 contains historical information on Crescent City for the time periods 1964 and 2000/2006. The reason for including the later years is to document some of the assumptions used in the benchmarking analysis (i.e., using HAZUS to estimate the effects of a large earthquake and tsunami considering today's building inventory). What is described in the table are 1) a tabulation of building assets in 1964 and 2000/2006; 2) hazard parameters (flow depths and velocities) based on a repeat of the 1964 Alaska Earthquake, as it affects Crescent City; and 3) damage totals from the 1964 earthquake, including deaths, injuries and estimated loss.

3.2 Damage Analysis

Table 19 shows a compilation of number of destroyed buildings in Crescent City during the Alaska earthquake. This summary was prepared using the digital maps discussed above. Of the 256 buildings that were identified as being located in tsunami flood areas, 63 were destroyed or about 25 percent. The percent of destroyed buildings by flow depth range (ft) is: 12 percent between 0 and 2 feet; 44 percent between 2 and 4 feet; 53 percent between 4 to 6 feet; and 100 percent between 6 and 8 feet.

Although there are markings on the map shown in Figure 29 that indicate damage to tanks and utility poles, this information was not considered in the present analysis. The details of the map were not clear enough to accurately discern the different lifeline components or the damage recorded to each after the tsunami.

Table 18: Historical Data and Assumptions used in a Repeat of the Alaska Earthquake affecting Crescent City

Category	Parameter	Observed Impacts from 1964 EQ	Notes / Assumptions
Inventory / Assets	Population [1964]	2,958	
	Population [2000]	8,110	
	Estimated # Buildings (1964)	1610	Hazus
	Estimated # Buildings (2006)	4,243	Hazus
	Estimated Exposure [1964 $M]	53	about 68% less buildings back then and assuming a 3% inflation
	Estimated Exposure (2006 $M)	570	Hazus
Hazard Assessment	Maximum Flood depth [ft]	10	At Harbor but predominantly 4 to 8 feet
	Estimated Maximum Velocity (ft/sec)	7 to 10	Based on Harry Yeh's Level 1 EQ's (P646)
	Estimated Maximum Flux [ft3/sec2]	150 to 250	Based on Harry Yeh's Level 1 EQ's (P646)
	Runup Height [ft]	13.7	First Wave
	# Damaging Waves	5	Literature
	Low Tide / High Tide	Low	5th Wave came at high tide
Damage Assessment and Impacts	Warning Time [minutes]	150	Up to when first wave hit
	Evacuation [%]	100	Evacuation started at about 90 minutes since warning issued
	Injuries	2	Trapped in 3rd wave
	Deaths	17	5 Trapped in 3rd wave and 12 swept away in 5th wave
	Inundated Buildings	256	
	Destroyed	63	
	Minor Damage	193	
	% Major Damage	24.6	
	Estimated Losses [1964 $M]	7.4	
	Estimated Losses [2006 $M]	25.9	

Table 19: Summary of Number of Buildings Destroyed as a Function of Flow Depth (feet) in Crescent City after the 1964 Alaska Earthquake

Damage State	Flow Depth (feet)				
	0-2	2-4	4-6	6-8 ft	Total
Not Destroyed	150	20	23	0	193
Destroyed	20	16	26	1	63
	170	36	49	1	256

3.3 Comparison with HAZUS Results

For purposes of performing our comparative analysis, the digitized file (Figure 27) containing flow depth contours was imported into HAZUS. The key parameters for the analysis are documented in Table 20. Flow depths (ft), run-up heights (R), maximum flow velocity (V), maximum flux (HV^2) and the probability of "Complete" damage are provided in Table 20.

Table 20: HAZUS Input Parameters

Flow Depth (ft)	Run-up Height (ft)	Flow Velocity (ft/s)	Flux (ft^3/s^2)	Probability of Complete Damage
2	13	4.0	21.4	0.0
4	13	5.6	65.4	0.04
6	13	6.9	132.1	0.20
8	13	7.9	221.4	0.44
10	13	8.9	333.4	0.66

A comparison of HAZUS results with the historical damage map shows the following positive observations:

- Estimated Damage
  - Number of buildings inundated (220) versus actual (256)
  - Number of completely damaged buildings (44 to 97) versus actual (63)
- Estimated Loss
  - $7.4M to $16M compared to reported loss ($7.4M)
  - Zero casualties with warning time of 150 minutes compared to actual (17 deaths, 2 injuries)
  - 222 deaths with warning time of only 10 minutes compared to actual (17 deaths, 2 injuries)

4. Recommendations and Conclusions

The following conclusions and recommendations are provided as a result of the present analysis.

1. Regional comparisons of loss and damage for both events (Tohoku and Alaska earthquakes) show considerable promise. The comparisons show that at aggregated levels, the results produced by HAZUS Tsunami are within a factor of 2, which is comparable to other pilot studies, e.g., Boston HAZUS Pilot Study. However, one important difference that must be reconciled between the HAZUS damage model for buildings and the Tohoku dataset is the notion that damage is either extensive or complete regardless of flow depth using the current HAZUS model. A strong recommendation of this report is to use the Tohoku data as a means of "re-calibrating" the HAZUS model for building damage. However, before any re-calibration is done, we strongly recommend that building damage data from other cities along the Northeastern coast of Japan be included.

2. While there are examples of "good" comparisons for some building and lifeline components, the majority of the evaluations show that the individual fragility or damage results must be improved. Whereas good results are demonstrated for wood-frame, residential construction and bridges (at least for the Tohoku case studies), most other comparisons show large differences between modeled and actual results. Unfortunately, in most of these cases, it is not clear whether the differences are due to real model deficiencies or whether the datasets used in the benchmarking analysis are too limited or being misinterpreted.

3. A preliminary analysis of the HAZUS casualty model suggests that the current model does a reasonable job in predicting the number of casualties for small block areas in Sendai and Kesennuma, i.e., order of magnitude consistency. However, very crude assumptions were made on the demographic make-up of each block area and the probable evacuation routes residents in each block would have taken given any pre-tsunami warning. In order to make a more meaningful assessment of the efficacy of the HAZUS casualty model, more data and more examples would have to be performed.

4. A major recommendation coming out of this study is to take advantage of the rich and extensive dataset that has been assembled for the 2011 Tohoku earthquake. In addition to damage data, inventory information (mainly for buildings) exists for many of the other cities affected by the earthquake. An inclusion of the larger dataset for the Tohoku Earthquake would allow the following investigations to be conducted:

    a. Validation of the trends suggested by the analyses conducted for Sendai and Kesennuma, or a clear indication that the current fragility models must be re-scaled or re-generated. For example, the assumption of smooth and proportional changes between damage states may not be correct and that a more reasonable assumption is that damage states fall into fewer categories, e.g., extensive/complete, slight/moderate.

    b. A finer analysis of the performance of lifeline components in general, and specifically, for particular lifeline types. For example, a larger dataset on gas systems might result in the development of equipment specific fragility datasets, e.g., storage tanks, electrical equipment, etc.

5. Because flow velocity and flux are key to the HAZUS methodology development, it is strongly recommended that the project team work with researchers currently examining flow velocity for the Tohoku earthquake to see if regional values can be estimated not only for the two areas studied in this report but for as many areas as possible that also contain the detailed MLIT damage data. And if such data are obtained, the project team suggests a more thorough analysis of damage and fragility trends using these additional hazard intensity indices.
6. The project team did the best that it could under the current time and resource constraints to fully understand the meaning of the Metadata provided in the MLIT database. It is certainly possible that some misinterpretation has occurred in the translation from Japanese to English. We recommend that more time and resources be provided in order to assemble a database that is consistent with U.S. and Japanese understanding of what the different damage descriptions are and what limitations should be recognized in order for more general public use of this data.
7. Normalizing the lifeline damage data is highly recommended, i.e., dividing damage results by the total population of facilities exposed to different flow depths whether or not they incurred damage. This will help to accurately scale effects and impacts so that a proper comparison with fragility functions can be made.
8. Where possible, earthquake data from events outside of the Tohoku and Alaska earthquake should be considered. The main benefit from this would be to ensure a more robust interpretation of the variability of these fragility functions. That is, different construction practices may or may not contribute to the damageability of buildings and lifelines. An inclusion of data from these other events will help to validate some of these assumptions.

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Appendix A: Aerial and Ground Photo Observations of Lifeline Damage in Sendai and Kesennuma

ID: 1
City: Sendai
Utility: Gas
Component Type: Manufacturing Facility
Location: 38.280067, 141.025228
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: Post event imagery from 4/6/11 shows no complete failure of structures within the facility. Piping has been repaired/replaced in imagery from 8/19/12 suggesting damage was repairable and not a complete loss. Intermediate imagery between the two dates shows no signs of demolition.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12
Bottom Left: Zoomed in view of broken piping (4/6/11). Bottom Right: Zoomed in view of repaired piping (8/9/12)

ID: 2
City: Sendai
Utility: Sewer
Component Type: Treatment Plant
Location: 38.249862, 141.005433
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Most structures still standing immediately following the event (imagery date 4/6/11), however, demolition of a few building and all tanks is apparent in imagery from 8/19/12.

Top Left: Pre-event imagery from 4/4/11. Top Right: Post-event imagery from 8/19/12), Bottom: Zoomed in view of post-event imagery showing demolition in process

ID: 3
City: Sendai
Utility: Sewer
Component Type: Pump Facility
Location: 38.249244, 140.988802
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: No heavy damage visible immediately following the tsunami. No sign of demolition. Appears skylight has been repaired and cars are in the lot suggesting building is functional (or soon to be).

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility (No heavy damage visible).

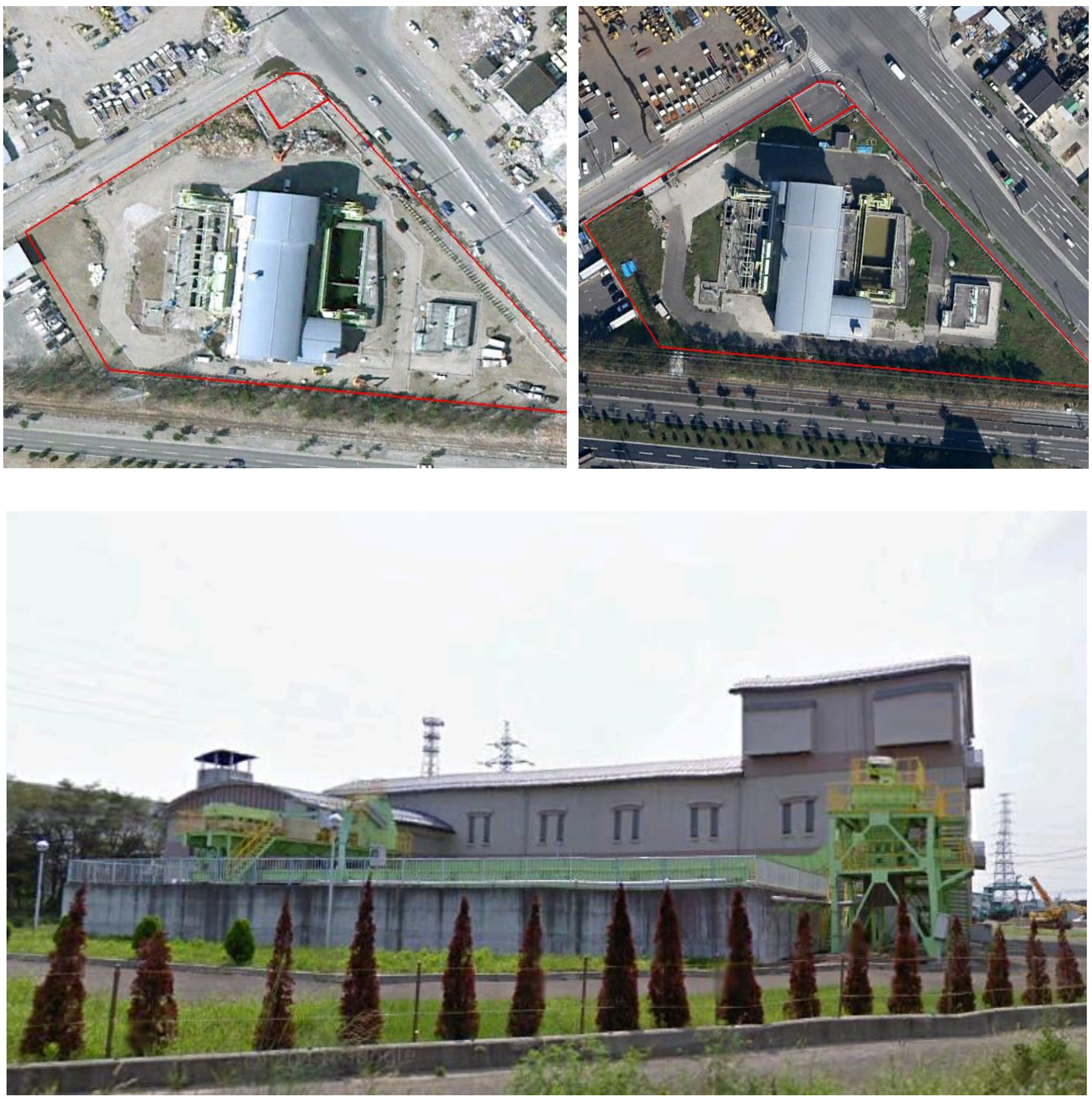
ID: 4
City: Sendai
Utility: Sewer
Component Type: Pump Facility
Location: 38.223013, 140.978329
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: Heavy damage following the tsunami, however it appears the structure has been repaired with no evidence of a demolition.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility (No heavy damage visible).

ID: 5
City: Sendai
Utility: Sewer
Component Type: Pump Facility
Location: 38.264552, 140.988409
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: Appears the structure has been repaired.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility (No heavy damage visible).

ID: 6
City: Sendai
Utility: Sewer
Component Type: Pump Facility
Location: 38.278000, 140.997651
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: No heavy damage evident post-disaster. Debris has been cleaned up and the structure appears to have been repaired from satellite imagery and ground photos.



Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility (No heavy damage visible).

ID: 7
City: Sendai
Utility: Water
Component Type: Specialty
Location: 38.256952, 141.003912
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Complete
Comments: Post-event imagery from 4/6/11 show heavy debris and a partially collapsed roof. No structures around survived. It appears the structures have been rebuilt from imagery taken on 8/19/12.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility

ID: 8
City: Sendai
Utility: Water
Component Type: Specialty
Location: 38.222011, 140.979788
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: Heavy debris surrounding the structure. It appears repairs have been made from post-event imagery and ground photos.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility (evidence of damage seen in roof)

ID: 9
City: Sendai
Utility: Water
Component Type: Specialty
Location: 38.278463, 140.997635
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Collapse based on post-event imagery (4/6/11) and ground photos (only the foundation remains). It has since been rebuilt, based on imagery from 8/9/12.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of remaining foundation

ID: 10
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.887920, 141.588383
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: The subject facility (and all surrounding) was washed away.

Left: Post-event imagery from 4/6/11. Right: Post-event imagery from 8/19/12.

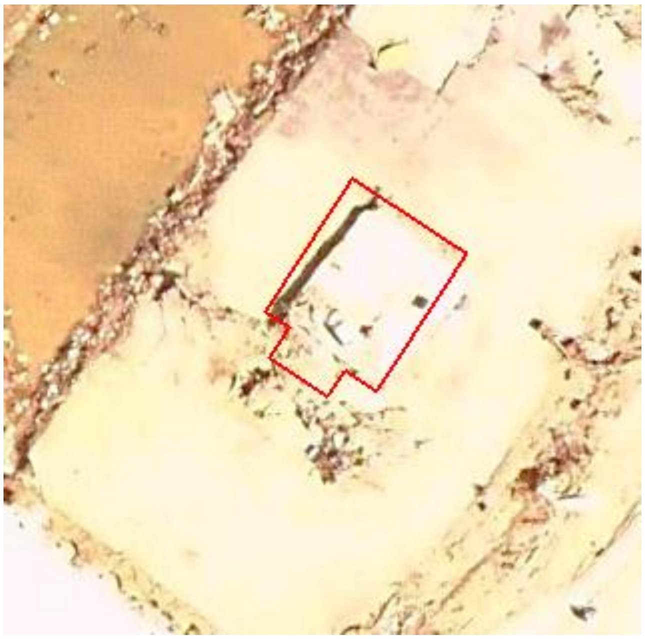
ID: 11
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.898185, 141.569515
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: No major damage visible immediately following the event. Structure appears to have been repaired (glass windows and doors not broken).

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 8/19/12.
Bottom: Ground photo of facility (no significant damage visible)

ID: 12
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.913924, 141.580977
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Structure showing signs of obvious collapse in post-event imagery.

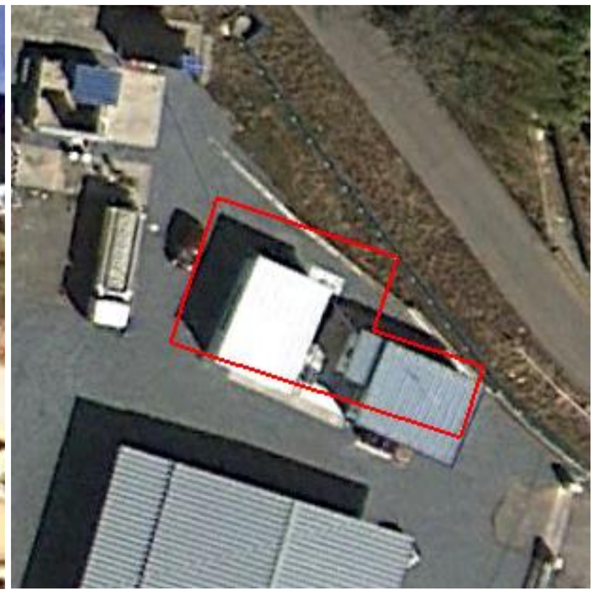
Left: Post-event imagery from 4/6/11. Right: Post-event imagery from 3/19/12.

ID: 13
City: Kesennuma
Utility: Gas
Component Type: Storage Facility
Location: 38.870825, 141.582060
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: The structure has almost been completely washed away as evident in the post-event imagery from 4/6/11. Imagery from 3/19/12 shows a rebuilt structure.

Left: Post-event imagery from 4/6/11. Right: Post-event imagery showing rebuilt facility from 3/19/12.

ID: 14
City: Kesennuma
Utility: Gas
Component Type: Storage Facility
Location: 38.809440, 141.553133
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Complete
Comments: No pre-event imagery is available for this area, however the structure shows a significant amount of damage in post-event imagery (4/6/11). Collapse of roof and exterior wall damage is visible. Imagery from 3/19/12 shows a rebuilt structure. Only the foundation is visible in street view.


Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12 showing rebuilt structure. Bottom: Post-event ground photo verifying complete loss (only the foundation is left)

ID: 15
City: Kesennuma
Utility: Gas
Component Type: Storage Facility
Location: 38.889966, 141.576775
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: The structure shows no evidence of catastrophic damage or demolition and reconstruction from satellite imagery ranging from 4/6/11 to 3/1912.

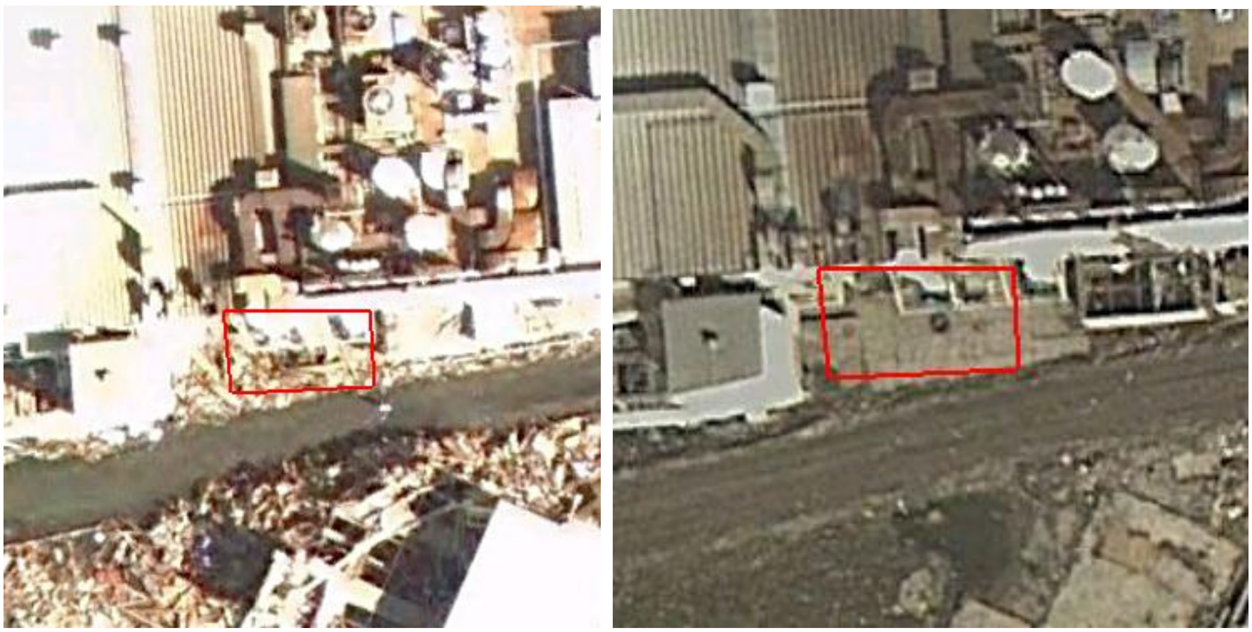


Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photo showing no major damage to the facility

ID: 16
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.895817, 141.581213
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: The component and surrounding structures have completely been washed away.

Left: Post-event imagery from 4/6/11 showing washed away facility. Right: Post-event imagery from 3/19/12.

ID: 17
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.910348, 141.584618
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Collapse of structure.



Left: Post-event imagery from 4/6/11 showing heavy debris. Right: Post-event imagery from 3/19/12.

ID: 18
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.905189, 141.572509
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: The structure is showing some signs of damage (surrounding debris, damaged roof, etc.) however appears to be salvageable based on ground photos and it's existence in post-event imagery from 3/9/12.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photo showing no catastrophic damage to the facility

ID: 19
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.895152, 141.573338
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: The component has been completely washed away.

Left: Post-event imagery from 4/6/11 showing washed away facility. Right: Post-event imagery from 3/19/12.

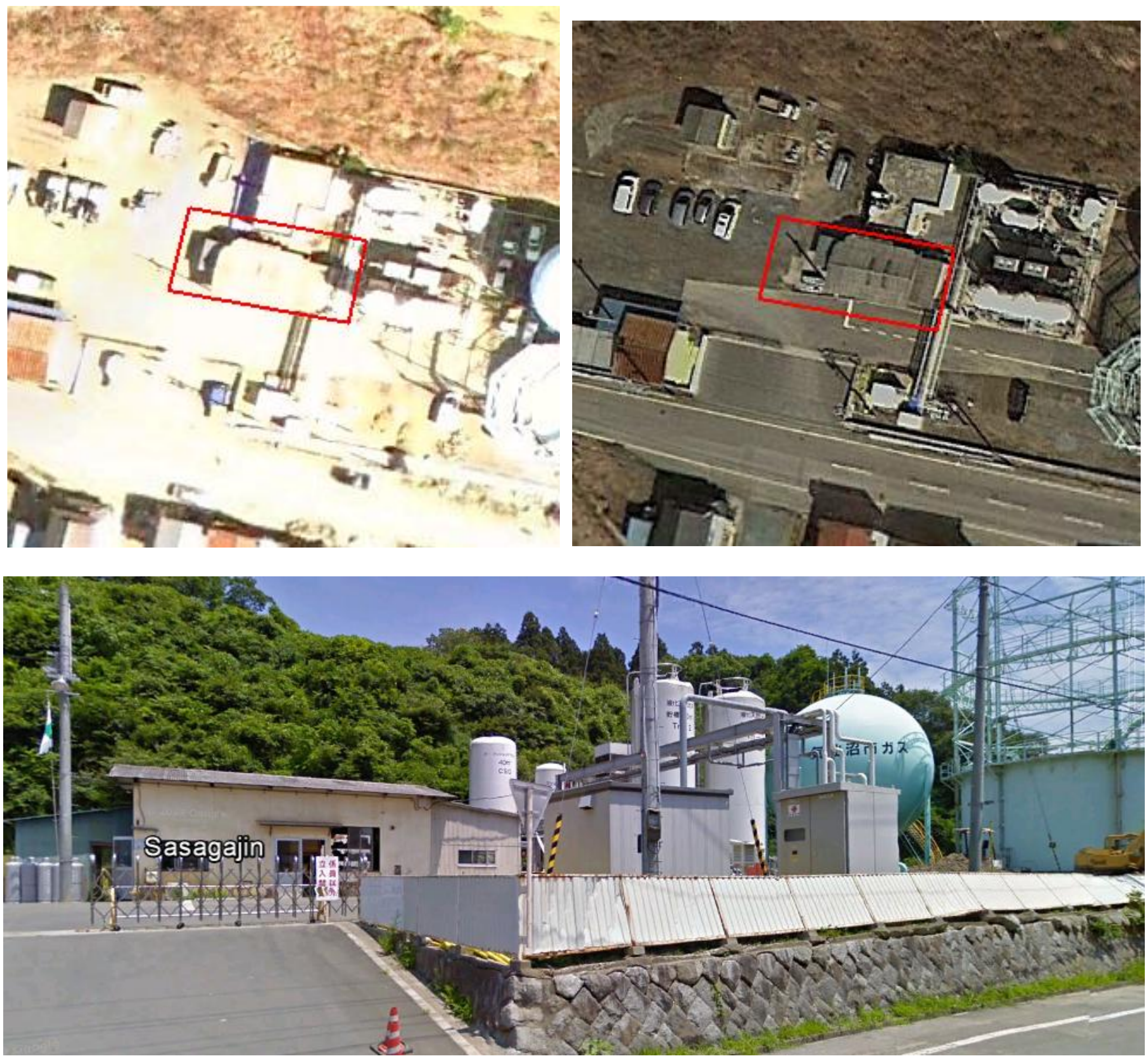
ID: 20
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.895979, 141.565641
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: No major damage visible. No observable change between satellite images. The structure was only subject to 0.6m of water, however not enough evidence is available to downgrade the damage to slight.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photo showing no major damage to the facility

ID: 21
City: Kesennuma
Utility: Gas
Component Type: Power Distribution
Location: 38.893194, 141.569104
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: No major damage visible. No observable change between satellite images.

Left: Post-event imagery from 4/6/11. Right: Post-event imagery from 3/19/12 (no observable changes).

ID: 22
City: Kesennuma
Utility: Gas
Component Type: Manufacturing Facility
Location: 38.898015, 141.570497
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: No major damage visible. No observable change between satellite images.

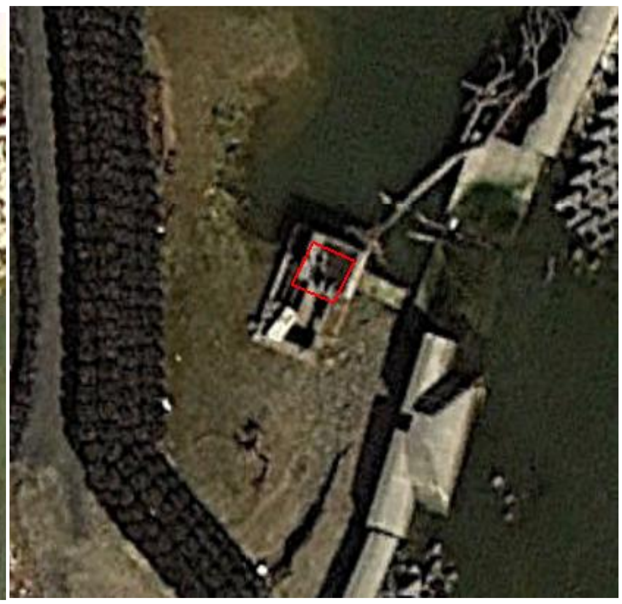


Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photo showing no major damage to the facility

ID: 23
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.886974, 141.605256
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Large amounts of debris in the area. All surrounding structures have been washed away.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photo showing area completely washed away.

ID: 24
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.867525, 141.585664
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Complete
Comments: No pre-event imagery is available for this area, however the structure was subject to 10m flow depths. Heavy debris is surrounding the structure and the tsunami wall is breached directly next to the pump facility. Post-event imagery from (3/16/12) still shows a collapsed roof and no obvious repair.



Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12 showing no obvious repairs
Bottom: Post-event ground photos showing extent of damage

ID: 25
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.757990, 141.519348
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Component and surrounding areas have been completely washed away.

Left: Post-event imagery showing washed away facility from 4/6/11. Right: Post-event imagery from 3/19/12.

ID: 26
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.867841, 141.606183
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): N/A
Comments: Component not visible.

Left: Post-event imagery from 4/6/11. Right: Post-event imagery from 3/19/12. Component is not visible.

ID: 27
City: Kesennuma
Utility: Sewer
Component Type: Treatment Plant
Location:
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: No catastrophic damage evident in imagery from 4/6/11. Debris surrounding has been cleaned up. No evidence of demolition.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12 showing no obvious repairs
Bottom: Post-event ground photos showing extent of damage

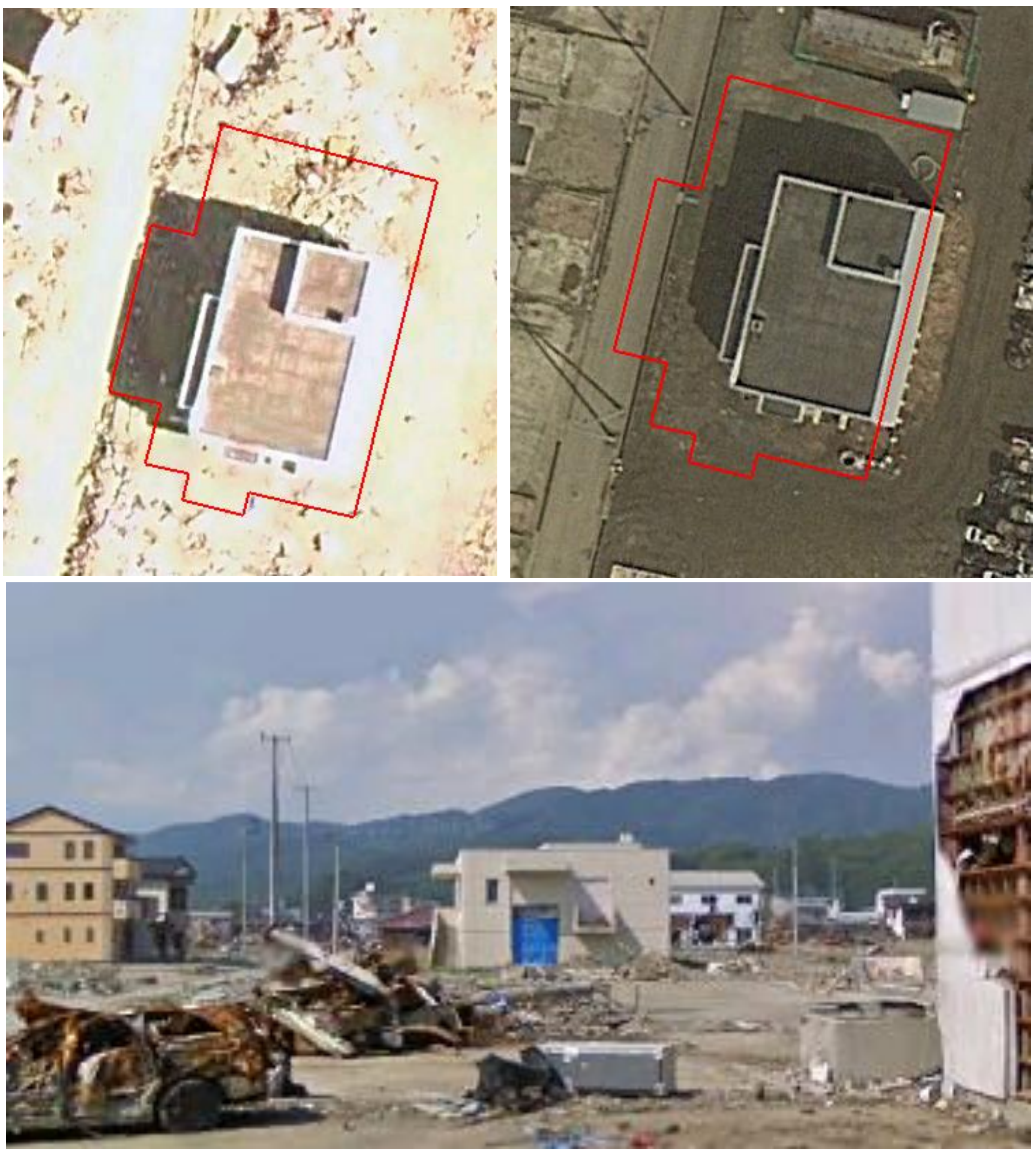
ID: 28
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.888106, 141.589260
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: Satellite imagery shows little damage to the structure. Ground photos show a large hole in one side of the exterior wall. A more appropriate damage state would be extensive.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing extent of damage

ID: 29
City: Kesennuma
Utility: Sewer
Component Type: Treatment Plant
Location: 38.895519, 141.583755
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Surrounding structures have been destroyed. Debris and standing water are still present in satellite imagery from 3/19/12, suggesting repair is not intended.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing standing water and extent of damage

ID: 30
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.916197, 141.582737
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: The surrounding structure has been cleaned up as evident in imagery from 3/19/12. No signs of a demolition are present, suggesting the building will be (or has been) repaired for use.

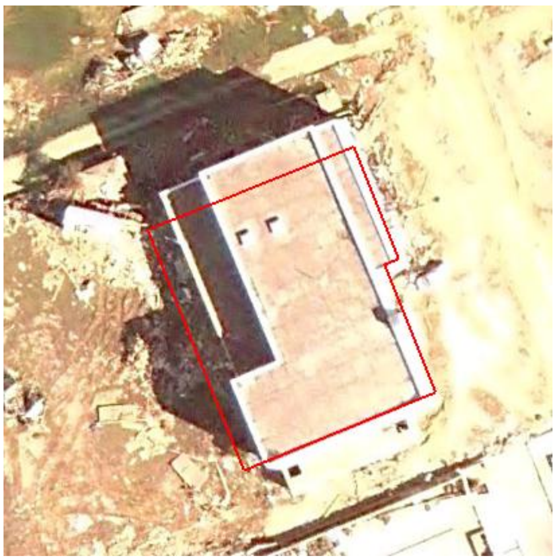


Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing surviving structure.

ID: 31
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.909633, 141.584455
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: Large amounts of debris surrounding the structure in post-event imagery from 4/6/11. Heavy roof damage and damage from debris is evident. The area has been cleaned up and the structure has not been demolished as of 3/19/12 based on satellite imagery.

Left: Post-event imagery from 4/6/11. Right: Post-event imagery from 3/19/12 showing clean-up.

ID: 32
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.872798, 141.587146
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: It is the only structure that survived around the area. Imagery 1 year after the event shows cleanup around building has occurred (no sign of demolition)



Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing extent of damage.

ID: 33
City: Kesennuma
Utility: Sewer
Component Type: Treatment Plant
Location: 38.785120, 141.499118
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: No catastrophic damage evident in post-event satellite imagery. Ground photos show the structure has remained relatively intact with no obvious damage.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing extent of damage.

ID: 34
City: Kesennuma
Utility: Sewer
Component Type: Treatment Plant
Location: 38.958770, 141.633073
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: The surrounding structures have all been completely washed away. This particular component has no visible catastrophic damage from post-event imagery.

Left: Post-event imagery from 4/1/11. Right: Post-event imagery from 3/1/12

ID: 35
City: Kesennuma
Utility: Sewer
Component Type: Treatment Plant
Location: 38.854738, 141.624756
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: No catastrophic damage evident immediately following the tsunami. Post-event imagery from 3/19/12 shows clean-up has occurred around the building. No evidence of a (potential) demolition is available.


Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing extent of damage.

ID: 36
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.892592, 141.599673
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Complete
Comments: An accurate assessment is difficult because of poor visibility (due to shadows and large amounts debris), however based on the performance of the surrounding structures, it is assumed the pump facility performed the same.

Satellite imagery showing the extent and degree of damage surrounding the facility.

ID: 37
City: Kesennuma
Utility: Sewer
Component Type: Pump Facility
Location: 38.893737, 141.585204
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: The structure has been demolished.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Ground photo showing the location of the destroyed facility.

ID: 38
City: Kesennuma
Utility: Water
Component Type: Intake Facility
Location: 38.907506, 141.553390
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: No catastrophic damage visible in post-event satellite imagery.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing extent of damage.

ID: 39
City: Kesennuma
Utility: Water
Component Type: Water Treatment Facility
Location:
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): Moderate
Comments: The structure does not appeared to have experienced complete damage. Pre- and post-event imagery verify it is still standing and a demolition has not occurred.

Top Left: Pre-event imagery from 11/4/09. Top Right: Post-event imagery from 4/6/11
Bottom: Post-event imagery from 2/22/12

ID: 40
City: Kesennuma
Utility: Water
Component Type: Specialty
Location: 38.778754, 141.494542
Damage Level (Japanese): Moderate
Damage Level (HAZUS Visual): N/A
Comments: Cannot determine the site of the component. Pre-event imagery shows an open plot of land.

Left: Pre-event imagery from 11/4/09. Right: Post-event imagery from 4/6/11

ID: 41
City: Kesennuma
Utility: Water
Component Type: Water Treatment Facility
Location: 38.823070, 141.575988
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Complete
Comments: Structure has been washed away.

Left: Pre-event imagery from 11/4/09. Right: Post-event imagery from 4/6/11.

ID: 42
City: Kesennuma
Utility: Water
Component Type: Specialty
Location: 38.919497, 141.581732
Damage Level (Japanese): Complete
Damage Level (HAZUS Visual): Moderate
Comments: The facility sustained heavy damage. “Extensive” would be more a more appropriate categorization. A moderate level is assigned because of its presence over a year after the tsunami occurred.

Top Left: Post-event imagery from 4/6/11. Top Right: Post-event imagery from 3/19/12.
Bottom: Post-event ground photos showing extent of damage.

Appendix B: Harry Yeh's Assumptions on applying casualty estimation methodology to Tohoku Earthquake

1. Consider this calculation as a very early and initial attempt for model "CALIBRATION." It is NOT a model validation.

2. I used the tuning multiplayer f_sub_T used in (4.8) = 1.5, instead of 2.0 suggested originally in "Hazard" Section. In fact, all other tuning multipliers should be calibrated. Any discrepancies from the data or judgment values could be corrected by adjusting such parameters as we originally planned (we just simply did not follow through our plan). In fact all of the comments by Ian R. could have been answered if we had not "skipped" our planned calibration phase of the project.

3. Detailed demographic data were not given except the total population. Hence, I simply used the data used in my original example: assuming 30% of population are adult males, 30% adult females, and 40% children --> the mean evacuation speed is 1.36 m/s, and the variance is 0.0464 (m/s)^2. This assumption is very likely incorrect, knowing the affected Japanese communities.

4. To compute Tmax, we should use the averaged value of the slope from the shore line to the maximum inundation. The distances from the shoreline were not given, hence I simply used the slope between the block of interest to the maximum run-up.

5. There are several parameters that should be calibrated. For example, C_sub_std in (8.8) is currently set 0.1, 0.3, and 0.5 for good, fair, and poor community preparation. This must be examined carefully. In this calculation, I did not change it: I used C-sub_std = 0.1 for a well prepared community.