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Benchmarking, Validation and Calibration of Newly-Developed HAZUS Tsunami Methodology

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Shunichi Koshimura[4], Fumio Yamazaki[5] and William P. Graf[6]

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This paper documents the results of an effort to benchmark modeling results generated from the newly-developed HAZUS Tsunami methodology. Although quantitative comparisons between HAZUS-modeled output and observations of damage from actual events are made, this analysis is considered preliminary in that data from only two events were used in the benchmarking process. Useful insights, however, are still possible, especially regarding whether the results appear to be in the right ballpark. At the end of this paper, we provide recommendations on improvements that should be considered in order to ensure effective application of the methodology in the U.S.

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This paper documents the results of an effort to benchmark modeling results generated from the newly-developed HAZUS Tsunami methodology. Although quantitative comparisons between HAZUS-modeled output and observations of damage from actual events are made, this analysis is considered preliminary in that data from only two events were used in the benchmarking process. Useful insights, however, are still possible, especially regarding whether the results appear to be in the right ballpark. At the end of this paper, we provide recommendations on improvements that should be considered in order to ensure effective application of the methodology in the U.S.

Introduction

This report documents the results of an effort to benchmark modeling results generated from the newly-developed HAZUS Tsunami methodology [1] and [7]. In our analysis, quantitative comparisons are made between HAZUS-modeled output, and observations of damage from actual events from two events: the 2011 Tohoku Earthquake and the 1964 Alaska Earthquake. Data for the Tohoku event was provided by the Japanese Government, City Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), published in March of 2012. Data for the Alaskan Earthquake is provided through a historical map obtained from Professor Lori Dengler of Humboldt University, which shows data from surveys conducted by the U.S. Army Corps of Engineers. Additional insights into this benchmarking study were provided in the following references: [2], [3], and [4].

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. The second objective focuses on calibration of damage and fragility

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models for buildings using the ground surveyed buildings in the Tohoku and Crescent City databases. In order to accomplish both tasks, 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.

Methodology and Assumptions

The methodology used in this study to perform the benchmarking task is illustrated in Fig. 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. A similar flowchart was produced for the Alaskan earthquake calibration. Data are in the form of building inventory databases (counts of buildings, building construction types, building footprint sizes, number of stories), hazard information (tsunami flow depths), and damage information (number of damaged buildings, damage levels). The white block modules are the HAZUS Tsunami calculation steps. Using the data on the Tohoku and Alaskan earthquake, HAZUS Tsunami calculates the number of damaged buildings by simulating a repeat of both events. The output is then compared with the actual damage totals and distributions generated from the field surveys conducted after the earthquake.

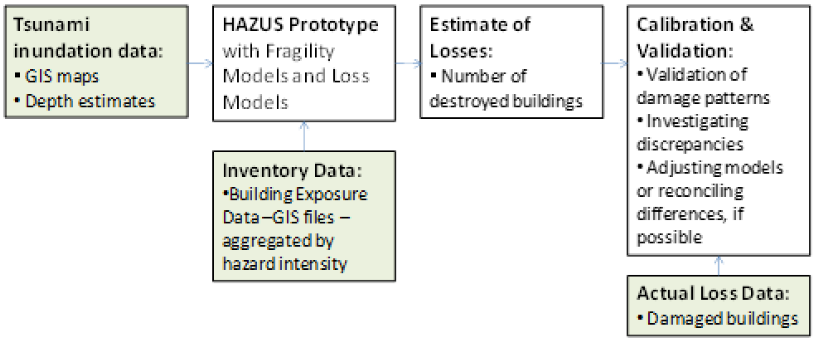

Figure 1. Benchmarking Flowchart for Tohoku, Japan Earthquake

2011 Tohoku Earthquake

Aggregated datasets for two study areas (Sendai and Kesennuma) were provided to the project team. 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. The following two data layers were provided to the team by MLIT through the Center for Spatial Information Science (CSIS) at the University of Tokyo:

- Building Database – provided as a .shp file and presented as building footprint outlines for Sendai and Kesennuma with 11,683 and 19,815 building records, respectively. The following information was available for each building footprint: occupancy, structural type, number of stories, and an assigned damage state.
- Maximum Tsunami Flow Depth – provided as a .shp file and presented as aggregate data in a 100 x 100 m grid cell system. The value associated with each grid is representative of the maximum flow depth within that cell. Building footprints were overlaid on this layer and the corresponding flow depths were then assigned to the footprint.

Damage Analysis

The Japanese data classified building 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. For HAZUS, damage is classified as one of the following four categories: slight, moderate, extensive and complete. The MLIT data provided for this analysis of building performance was used as received. That is, no attempt was made to check/validate these datasets.

Table 1 shows how the Japanese damage descriptions were mapped into the HAZUS damage categories.

Table 1. 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	

The distribution of buildings by damage state and flow depth is shown in Tables 2 and 3 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). 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 and over 75% suffering complete damage.

To study the variation of each damage state as a function of flow depth, Fig. 2 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.

Table 2. 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 3. 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

A plot of damage state frequencies by flow depth for Kesennuma shows a very different trend than for Sendai. Rather than showing nice central values for each damage state (as demonstrated with the Sendai data), the curves in Fig. 2 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, flow velocities in Kesennuma (outflow velocity in Kesennuma Bay estimated at 11m/s [5]) were much higher than in Sendai (flow velocity estimated at about 6 m/s for Sendai plain [6]). 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.

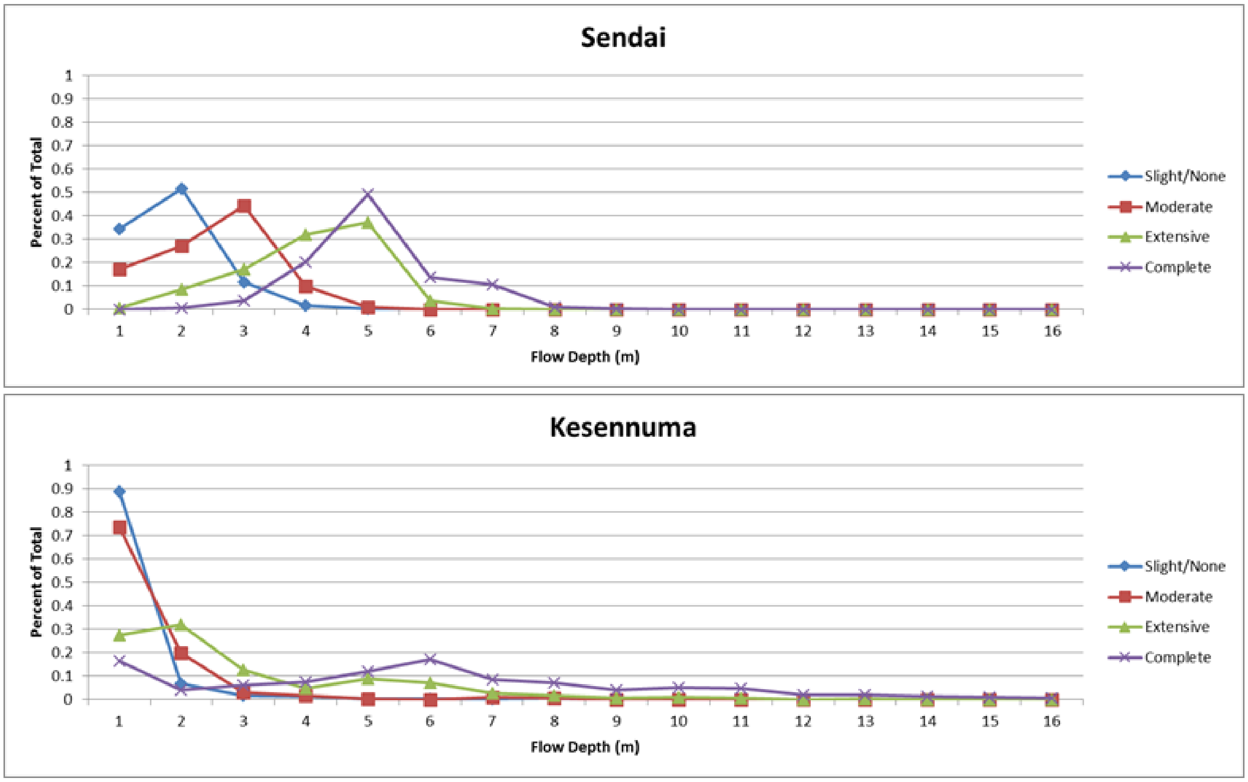

Figure 2. Distribution of Damage States by Flow Depth for Sendai and Kesennuma

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

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

Table 4. 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 5. Modeled Results for Kesennuma

Damage State	Flow Depth (meters)					
	0-3	3-6	6-9	9-12	12-15	Total
Extensive	6	.2265	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

Fig. 3 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.

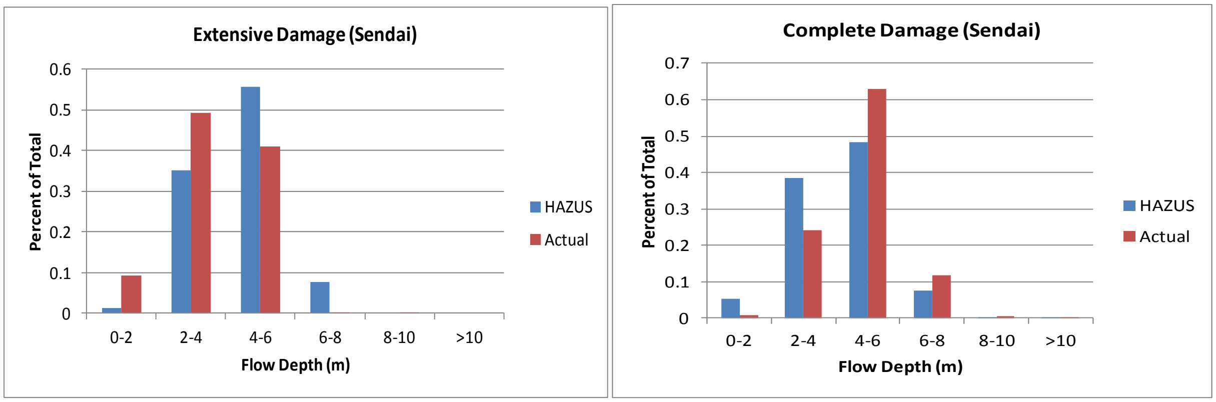

Figure 3. Comparison of Predicted versus Actual Observations of Building Damage for Sendai

Fig. 4 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.

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 [4].

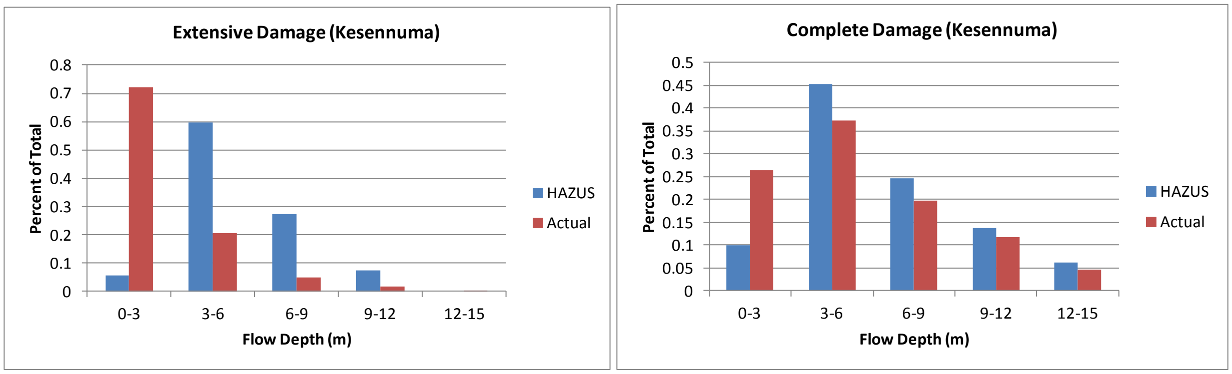

Figure 4. Comparison of Predicted versus Actual Observations of Building Damage for Kesennuma

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.

A historical map 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. Fig. 5 shows the digitized version of the historical map.

Table 6 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.

Damage Analysis

Table 7 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.

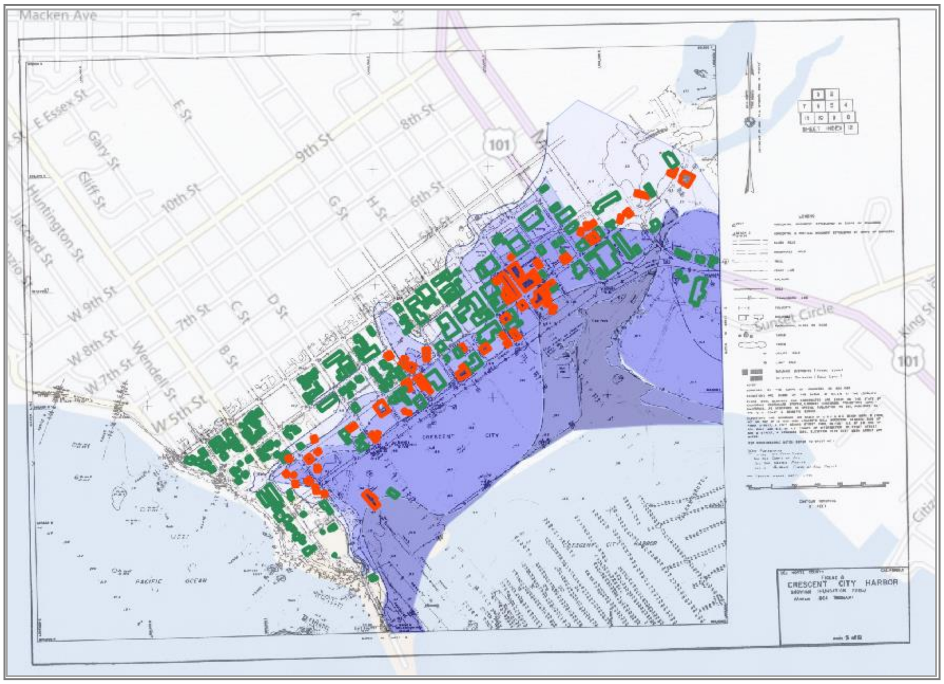

Figure 5. Digitized Version of Historical Map with Footprints and Inundation Lines Digitized, Geo-referenced and Overlaid on Bing Maps. Red outlines delineate destroyed structures.

Table 6. 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 7. 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

Comparison with HAZUS Results

For purposes of performing our comparative analysis, the digitized file (Fig. 5) containing flow depth contours was imported into HAZUS. The key parameters for the analysis are documented in Table 8. 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 8.

Table 8. 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)

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. 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.

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